Multitemporal spectroradiometry-guided object-oriented classification of salt marsh vegetation

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ABSTRACT

This study addresses the use of multitemporal field spectral data, satellite imagery, and LiDAR top of canopy data to classify and map common salt marsh plant communities. Visible to near-infrared (VNIR) reflectance spectra were measured in the field to assess the phenological variability of the dominant species − *Spartina patens*, *Phragmites australis* and *Typha* spp. The field spectra and single date LiDAR canopy height data were used to define an object-oriented classification methodology for the plant communities in multitemporal QuickBird imagery. The classification was validated using an extensive field inventory of marsh species. Overall classification accuracies were 97% for *Phragmites*, 63% for *Typha* spp. and 80% for *S. patens* meadows. Using a fuzzy assessment analysis, these accuracies were 97%, 76%, and 92%, respectively, for the three major species.

Keywords: salt marsh; vegetation monitoring; image classification; *Phragmites australis*; QuickBird; LiDAR; spectroradiometer, image segmentation, Connecticut

1. INTRODUCTION

Coastal wetlands are a critical component of the Long Island Sound ecosystem. Over the past century, a significant amount of these wetlands has been lost due to development, filling and dredging, or damaged due to human disturbance and modification. Global sea level rise is also likely to have a significant impact on the condition and health of coastal wetlands, particularly if the wetlands have no place to migrate. In addition to physical loss of marshes, the species composition of marsh communities is changing. *Spartina alterniflora* (salt cordgrass) and *Spartina patens* (salt marsh hay), once the dominant species of New England salt marshes, are being replaced by monocultures of the non-native genotype of *Phragmites australis* (common reed) in Connecticut marshes [1]. With the mounting pressures on coastal wetland areas, it is becoming increasingly important to identify and inventory the current extent and condition of coastal marshes located on the Long Island Sound estuary, implement a cost effective way to track changes in wetlands over time, and monitor the effects of habitat restoration and management. The ultimate goal of this project is to provide protocols that can be used to classify multispectral data readily available to land managers.

The identification of the distribution and health of individual marsh plant species like *Phragmites* using remote sensing is challenging because vegetation spectra are generally similar to one another throughout the visible to near-infrared (VNIR) and the spectrum of a single species may vary throughout the growing season due to variations in the amount and ratios of plant pigments, leaf water content, plant height, canopy effects, leaf angle distribution and other structural characteristics. While vegetation phenology has long been recognized to be useful in discriminating species for vegetation mapping [2,3], most classification methodologies applied to wetlands have been based on image and/or ground reference data measured on a single date which limits their applicability to images taken at other times. Previous work on the classification of marsh vegetation using multitemporal image [4,5,6] and LiDAR [7] data relies on identification of endmembers, often derived from extensive field measurements. Such field measurements may be impractical if a goal is to inventory vegetation in even a small number of marshes. In this work, we take a different approach, testing a new method to relate field measurements at a limited number of sites to image classification.

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Here we report on an approach where VNIR reflectance spectra of marsh vegetation measured in the field over the growing season were used to guide the classification of high spatial resolution multitemporal QuickBird data. Single date LiDAR data also contributed to the classification. We sought to: 1) determine the optimal times during the growing season for the discrimination of individual marsh plant species based on spectral reflectance and structure measured in the field, and 2) assess the utility of these field data to direct the classification of multitemporal images of the entire marsh, with particular attention to the mapping of the invasive species *Phragmites*. Our overall goal was to provide protocols that can be used to classify multiple or single date multispectral data that are available to wetland managers.

2. METHODS

2.1 Study Sites

Ragged Rock Creek marsh is a 142 hectare brackish tidal marsh located on the western shore of the Connecticut River, approximately 2.5 km north of its confluence with Long Island Sound (Fig. 1). The vegetation at Ragged Rock Creek marsh is typical of Connecticut's estuarine tidal marshes, where the pattern of growth is generally controlled by salinity, a function of duration and magnitude of tidal inundation, and therefore elevation. The vegetation at Ragged Rock Creek marsh is a mosaic, ranging from patches of monospecific dominants with discrete boundaries, to mixed-species patches with more diffuse transitions. While our field survey identified 115 plant species at Ragged Rock Creek marsh, the vegetation was dominated by three communities: 1) salt meadow grass (*Spartina patens*) often mixed with spike rushes (*Eleocharis* species). 2) narrow-leaved cattail (*Typha angustifolia*) and hybrid cattail (*Typha* x *glauca*) and 3) non-native common reed (*Phragmites australis*) occupied the mid-to high-marsh areas and upper border, typically forming dense monotypic stands. The distribution of *Phragmites* was strongly correlated to the mosquito ditches that exist throughout the marsh. *Spartina alterniflora*, a common species in salt marshes of Connecticut, is not abundant in the study area and was not inventoried.

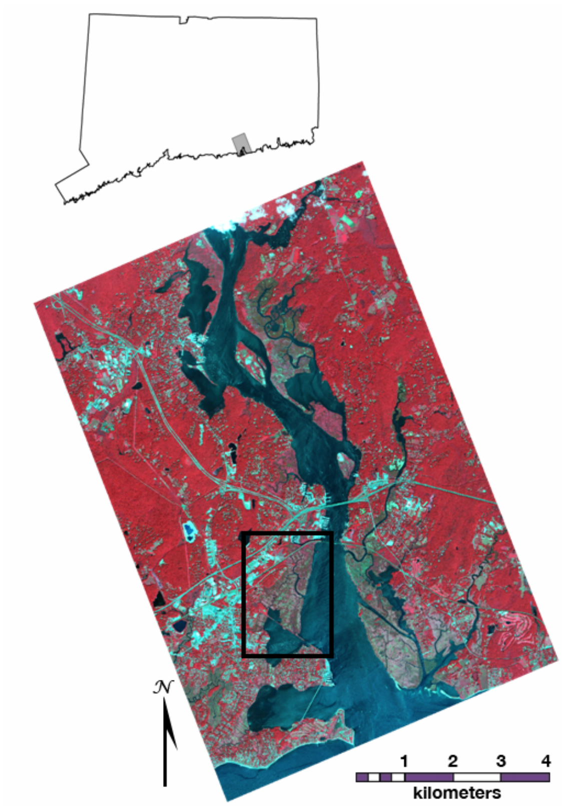

Fig. 1. Location of Ragged Rock Creek marsh, Old Saybrook, Connecticut (USA). July 20, 2004 QuickBird image (Bands 4,2,1) of the mouth of the CT River, inset refers to location of study site in Fig. 2.

2.2 Spectral Data Collection and Processing

Reflectance spectra were obtained using an ASD Fieldspec FR® spectroradiometer (Analytical Spectral Devices, Boulder, CO) with a wavelength range of 0.35 to 2.50 µm. Individual spectral measurements were an average of 5 - 10 scans and each canopy was generally sampled 10 or more times. These samples were then averaged to provide a single spectrum for each target for which a standard deviation was calculated. Reflectance spectra were normalized to a white Spectralon® (Labsphere, Inc., North Sutton, NH) panel.

Reflectance spectra were collected for the three dominant vegetation communities at two sites in Ragged Rock Creek marsh (Fig. 2): *Spartina patens* meadows (*S. patens* ± *Eleocharis* spp., hereafter referred to as *S. patens*), *Typha* spp. (*Typha angustifolia* and/or *Typha* x *glauca*) and *Phragmites australis*. To document between- and within-plant phenology, field spectra were collected from specific stands of each of the three plant communities monthly in the summer of 2004 at Site 1, approximately biweekly at Site 2 in the summer of 2005 and on a single date in the fall of 2006 (Table 1). The selected stands were dense monocultures so as to approximate best species' endmember characteristics.

To correlate better the field spectra to QuickBird satellite data, individual field reflectance spectra were averaged over the four QuickBird band intervals (Band 1 (blue): 0.45-0.52 µm, Band 2 (green): 0.52-0.60 µm, Band 3 (red): 0.63-0.69 µm and Band 4 (NIR): 0.76-0.90 µm (Fig. 3) to produce a simulated QuickBird band value. From these data, four spectral indices were found to be most useful for discrimination of species: 1) green/blue, 2) NIR/red, 3) red/green, and 4) the Normalized Difference Vegetation Index (NDVI = (NIR – red)/(NIR + red)). The values of these indices over the growing season comprise a set of “radiometry rules” that were used to guide image segmentation and classification. Vegetation indices were used for classification instead of raw bands because they reduce data volume, provide information not available in a single band [8], and normalize differences in reflectance when using multiple images [9] and when comparing field and satellite data.

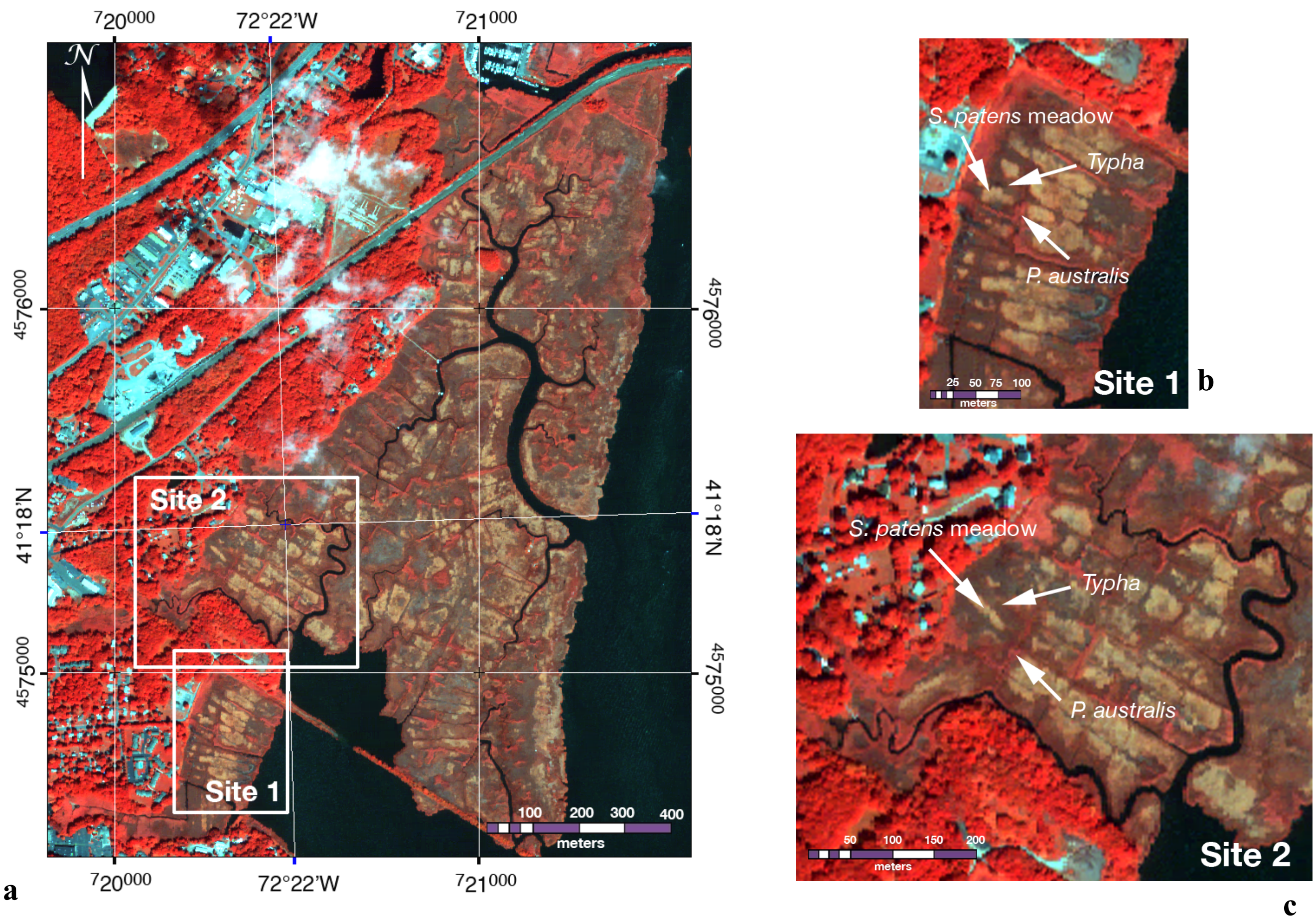

Fig. 2. September 12, 2004 4-2-1 QuickBird image of Ragged Rock Creek marsh, (a) overview of marsh, (b) Site 1, (c) Site 2. Arrows indicate approximate areas where reflectance spectra were measured in the field throughout the growing season. Spectra were measured at Site 1 in 2004 and Site 2 in 2005.

2.3 Validation Data

A floristic inventory of the marsh was conducted throughout the summer of 2006, in large part to establish sets of training and validation data for image classification work. A set of 1,000 randomly distributed point locations within the marsh was generated. At each location, 4 m^2 quadrats were placed and plant community composition and species abundance were recorded. Field GPS coordinates for each sampling site were recorded using Trimble GeoExplorer3 GPS units and were post-processed to improve accuracy using Trimble GPS Pathfinder Office, or coordinates were recorded using Garmin Map 76CSx GPS coupled with a CSI-Wireless MBX-3S Differential Beacon Receiver for enhanced accuracy using real-time differential correction. Data collected at each sampling site included: species present, estimated percent cover for each species, height of dominant species, and sociability rank for each species based on its distribution (*e.g.*, tightly clustered in one area *vs*. distributed throughout) across the plot. Digital photographs also were taken at each site to document field conditions at the time the inventory was conducted. In total, 923 vegetation plots were recorded at Ragged Rock Creek; 877 were random plot locations and 46 were subjective plot locations opportunistically selected by the field teams as being unusual, rare or monotypic plant communities. Some plots were revisited during the growing season; only one data point was maintained for each plot location resulting in a grand total of 917 field points. For the purposes of image classification accuracy assessment, all points were assigned to one of five dominant classes: *Phragmites*, *Typha* spp., *S. patens*, Water, and Other/mixed to correspond with the classification.

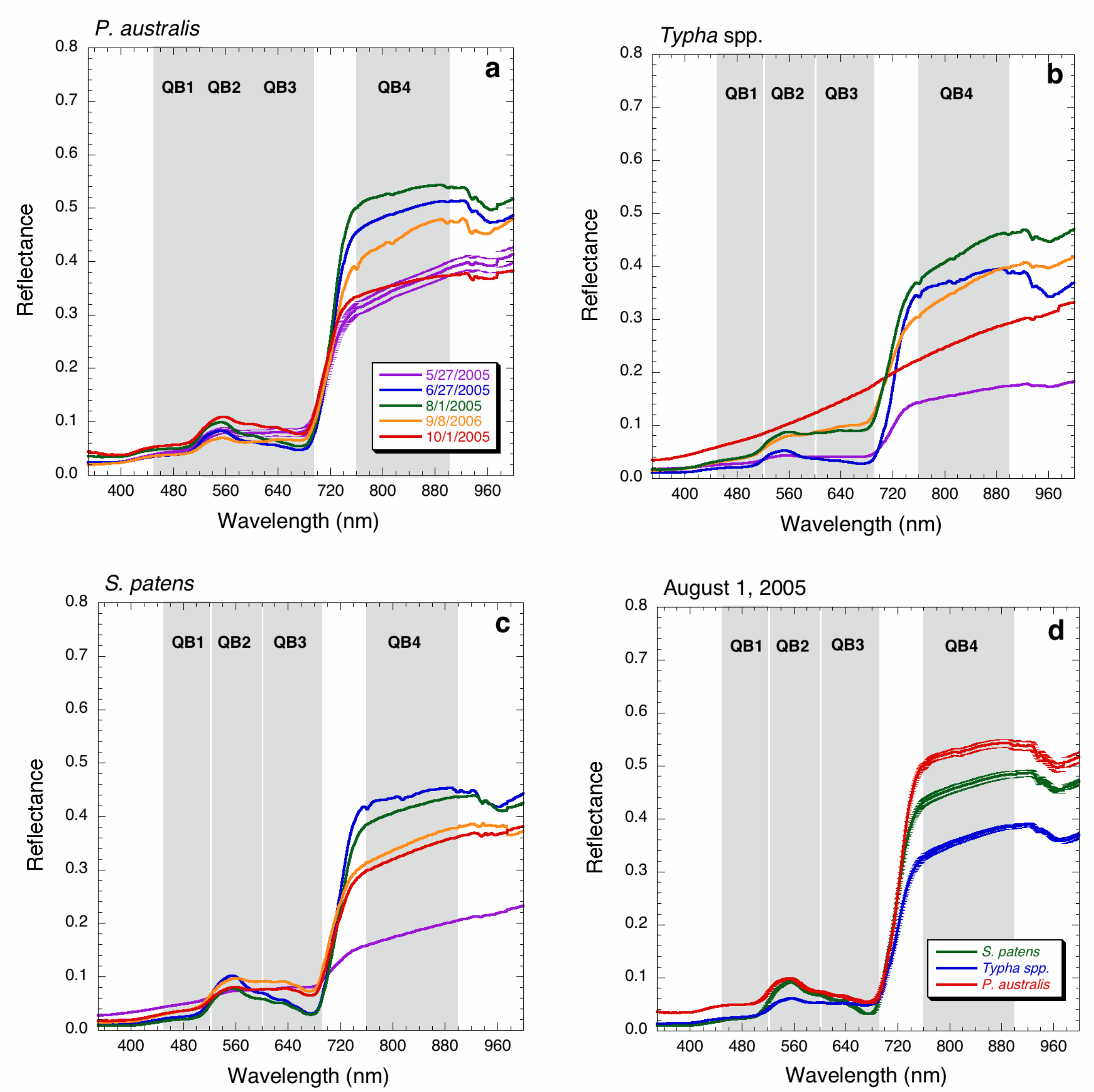

Fig. 3. Example reflectance spectra of major plant species in Ragged Rock Creek marsh. Each spectrum is an average of ≥10 spectra. QuickBird band positions are indicated. Collection sites indicated in Figure 2c. Spectra of (a) *Phragmites*, (b) *Typha* spp., and (c) *S. patens* throughout the growing season. Key in Figure (a) corresponds to Figures (b) and (c). One standard deviation of the averaged spectra is plotted for *Phragmites* on May 27, 2005 in (a) and is typical of the reflectance data shown in all panels. (d) Spectra of major marsh plant communities on August 1, 2005. One standard deviation of the averaged spectra is plotted.

2.4 Image and LiDAR processing

QuickBird satellite image data (2.44-meter at nadir) were acquired for a 100 km^2 area at the mouth of the Connecticut River (Fig. 1) on nine dates from July 2003 through November 2006 (Table 1). Each of the images was co-registered to the July 20, 2004 QuickBird image (UTM coordinate system, WGS84 datum, Zone 18) to assure consistent alignment. Of the nine scenes, five (Table 1, **red**) were selected for the final classification based on image quality (lack of clouds and haze), acquisition month and day, and importance as determined by field spectra data analysis. Although the images spanned several growing seasons, the month and day of acquisition was considered more important than the year of acquisition because the monthly spectral variability was observed to be much greater than interannual variability in the data set.

Multiple return LiDAR data were collected on October 8, 2004 at an altitude of 3,000 feet using a Leica ALS50 airborne laser scanner. First and last returns were recorded. The LiDAR data points had a nominal ground sampling distance of 0.9 m and a reported horizontal accuracy of 0.5 m. Based on 22 points, the average error between the bare earth LiDAR coverage and the control was 0.002 m with an RMSE of 0.057 m. LiDAR non-ground data points for the project area were reprojected to UTM Zone 18N, NAD83, meters and were converted to a 2.4 m resolution elevation grid using the Natural Neighbors interpolator in the 3D Analyst Extension to ArcGIS. The elevation grid was converted to an 8-bit unsigned integer format for use in the eCognition™ (Definiens AG, Trappentreustrasse, 80339, München, Germany) software. The elevation grid approximated the top of the plant canopy within the study area.

Table 1. Dates of data acquisition at Ragged Rock Creek Marsh. **Black** and **red** typeface indicates QuickBird image collection **(red** dates indicate the Quickbird images used in classification), **green** typeface indicates field spectra collection, **blue** indicates airborne LIDAR data collection.

Year	May	June	July	Aug	Sept	Oct
2004	**14**	**15**	**14**	**19**	**21**	
	27		**2** **20**		**12**	**8**
2005	**27**	**9** **27**	**13**	**1** **12** **26**	**9**	**1**
		2 **17**	**23**			
2006	← Vegetation Survey		**31**	**13**	**8** →	

2.5 Classification

Classification was conducted using the object-oriented image analysis software eCognition™, which allows for a variety of image and other data types to be added as input layers to a project file. Input data consisted of individual QuickBird bands from a single date, multiple date band ratios, and LiDAR top of canopy information. A polygon of the Ragged Rock Creek marsh was created and used to eliminate non-marsh features such as houses, trees and lawns from the input data. The input data were segmented into image objects, which are contiguous pixels that are grouped together into homogeneous polygon features. Spectral and spatial parameters (smoothness and compactness) were set to contribute 70 percent and 30 percent, respectively, to the segment boundary definition. The relative size of each image object is determined by a scale parameter, which sets the maximum allowed heterogeneity between image objects. A scale parameter of 20 was found to be the optimum size to best identify the plant communities within the Ragged Rock Creek marsh using QuickBird data.

2.6 Accuracy Assessment

Two-thirds of the field points from the floristic inventory (n = 613) were used for accuracy assessment, but only those that were at a distance greater than two meters (n = 379) from each class boundary were used to ensure that the points were located within the class being evaluated and that GPS inaccuracies and image registration errors were not factors. The accuracy assessment used a fuzzy set approach [10] resulting in five tables conveying the frequency, magnitude, source, and nature of mapping error. Fuzzy sets acknowledge the inherent variation in vegetation communities by allowing for sites to exhibit some grade of membership among map classes. For example, sites may reasonably be members of multiple classes, or alternately, some sites may only show a poor resemblance to any of the map classes.

At each site, the Euclidean distances in ordination space to all vegetation class centroids [11, 12] were inversely translated into ordinal ranks from 1 to 5, corresponding to the five linguistic levels of Gopal and Woodcock's [10] rating system of increasing correctness, labeled: 1) Absolutely Wrong, 2) Understandable but Wrong, 3) Reasonable or Acceptable Answer, 4) Good Answer, and 5) Absolutely Correct. Additionally, "expert" judgment was made, without the analyst's knowledge of the map labels, to make adjustments in linguistic fuzzy values for the conspicuous dominance or absence of major species. The result was a matrix where each field point had a value between 1 and 5 assigned to each of the four potential classes. The accuracy assessment was completed by comparing the vegetation class rating of each sample site to the QuickBird classification result.

3. RESULTS

3.1 Radiometry

The canopy reflectance spectra of each plant community were broadly similar, including absorptions typical of healthy photosynthesizing vascular plants (Fig. 3). At the beginning of the growing season, each spectrum showed expected increases in the strength of the absorptions at approximately 0.45 μm and 0.68 μm and an increase in NIR reflectance. This trend continued in each species until the onset of senescence (Fig. 3a). Comparison of the spectra of individual species showed that the magnitude and shape of the spectra can differ qualitatively on individual dates (Fig. 3b).

To relate the spectral variability of the field data to QuickBird images, the reflectance spectra of each species were reduced to QuickBird band ratios and plotted as a function of average accumulated growing degree days (GDD_{50} = (average daily temperature – 50°F)) using temperature data records for the Groton, CT airport acquired by the National Climatic Data Center (Fig. 4). The spectral behavior of the three marsh plant communities at the two field sites was broadly consistent over the growing seasons. Trends of NDVI and the NIR/red ratios were similar to each other, where the NIR/red ratio provides greater separability among the individual points (Fig. 4a,b). All species demonstrated a rise in these indices at approximately GDD_{50} 400 (early June) corresponding with the green-up phase of plant growth and a subsequent decline in the indices corresponding to senescence. The behavior of the seasonal variation in each index varied with plant species: *S. patens* and *Phragmites* reached peak values at ~ $GDD_{50} \geq 900$ and *Typha* spp. at ~GDD_{50} 500. NDVI and NIR/red values for *Typha* spp. were generally higher than the other species near the time of their peak (mid-to late June), while *Phragmites* values exceeded the other species in mid-August through early September.

The seasonal pattern of the QuickBird green/blue ratio of *S. patens* was distinct from the other two species (Fig. 4c). Values of this ratio were similar for each species at the beginning of the season, but *S. patens* rose to a peak value near GDD_{50} 900 (mid-July). The absolute value for *S. patens* was twice that of *Typha* spp. and *Phragmites* from early June through early August.

The general seasonal pattern of the QuickBird red/green ratio for all species showed an initial decline from approximately GDD_{50} 200 to GDD_{50} 800 (late May – late June) and then an increase (Fig. 4d). *S. patens* values in this index were lower than the other two species over GDD_{50} 400 to 1500 (mid-June – early August). *Typha* spp. values exceeded those of the other species from mid-July onward.

Three simple band ratios were determined to be most useful in identifying at least one major plant community: for *Phragmites*−the NIR/red ratio in late summer, for *S. patens*−the green/blue ratio in midsummer, and for *Typha* spp.−the red/green ratio in late summer (circled points, Fig. 4). These periods showed both the greatest spectral separability among species **and** the best correspondence with the dates (month, day) of the QuickBird images available for classification (Table 1; Fig. 4).

On the Ragged Rock Creek marsh, the average height of *Phragmites* determined from the field survey points was 2.1 meters (n = 213), *Typha* spp. points averaged 1.1 meters (n = 206) and *S. patens* points averaged 0.7 meters (n = 160; Fig. 5). The LiDAR data generally agreed with field observations of each species' growth habit in October.

3.2 QuickBird Classification

Figure 6 graphically illustrates the rules that were identified from the field spectra and implemented in the classification of the QuickBird images (Fig. 7). Qualitatively, the classification identified contiguous areas of *Phragmites*, *Typha* spp., and *S. patens*. The distribution of these classes was broadly consistent with field observations, for example, the correspondence of *Phragmites* and negative correspondence of *S. patens* with creeks and ditches. The classification confirmed that the portion of Ragged Rock Creek marsh surveyed was dominated by the three species under study, where classified *Typha* spp. and *Phragmites*, comprised 36% (45.2 hectares) and 24% (30.5 hectares) respectively, *S. patens* covered 22% (27.8 hectares), and other species covered 18% (22.9 hectares) of the marsh.

A fuzzy accuracy measure for each map class and the overall (total) map were determined by the frequency of correct matches (and mismatches) using two fuzzy accuracy measures, MAX and RIGHT (Table 2). The MAX column indicates the strictest measure of accuracy where only the highest membership level was acceptable and is the closest measure to traditional accuracy assessment [13]. The RIGHT column indicates an acceptable map label choice (a rating level of ≥ 3). *Phragmites* had the highest accuracy with both MAX and RIGHT at 97%. *Typha* spp. was the least accurate with 63% MAX and 76% RIGHT. The *S. patens* meadows type was labeled correctly in most cases with a MAX of 80% and RIGHT of 92%. The category Other/Mix had a MAX value of 72% but a RIGHT value of 100%, showing the greatest improvement of 28%. In general, the total weighted accuracy of all map labels adjusted for areal proportion of each map class had a MAX rating of nearly 77% and an acceptable RIGHT rating of nearly 89%.

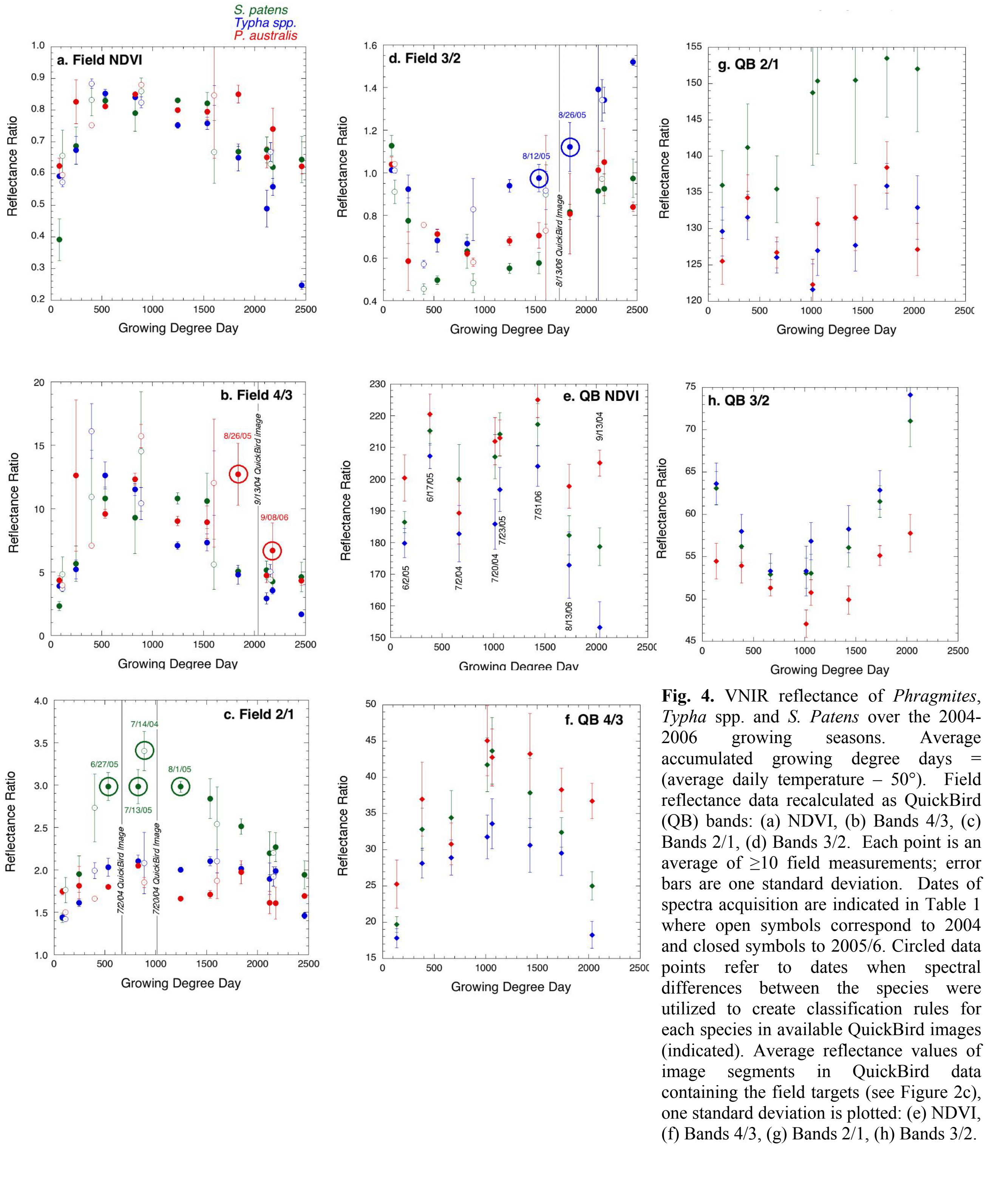

Fig. 4. VNIR reflectance of *Phragmites*, *Typha* spp. and *S. Patens* over the 2004-2006 growing seasons. Average accumulated growing degree days = (average daily temperature – 50°). Field reflectance data recalculated as QuickBird (QB) bands: (a) NDVI, (b) Bands 4/3, (c) Bands 2/1, (d) Bands 3/2. Each point is an average of ≥10 field measurements; error bars are one standard deviation. Dates of spectra acquisition are indicated in Table 1 where open symbols correspond to 2004 and closed symbols to 2005/6. Circled data points refer to dates when spectral differences between the species were utilized to create classification rules for each species in available QuickBird images (indicated). Average reflectance values of image segments in QuickBird data containing the field targets (see Figure 2c), one standard deviation is plotted: (e) NDVI, (f) Bands 4/3, (g) Bands 2/1, (h) Bands 3/2.

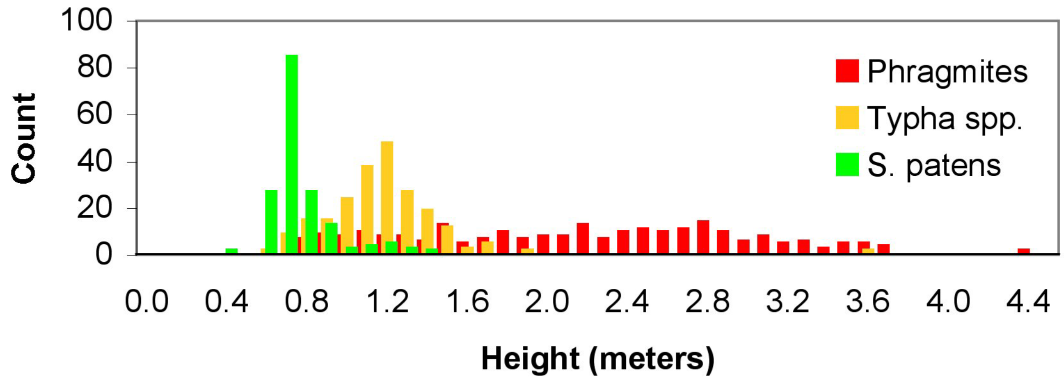

Fig. 5. Histograms showing LiDAR height data for GPS field inventory plots where each plant class is dominant.

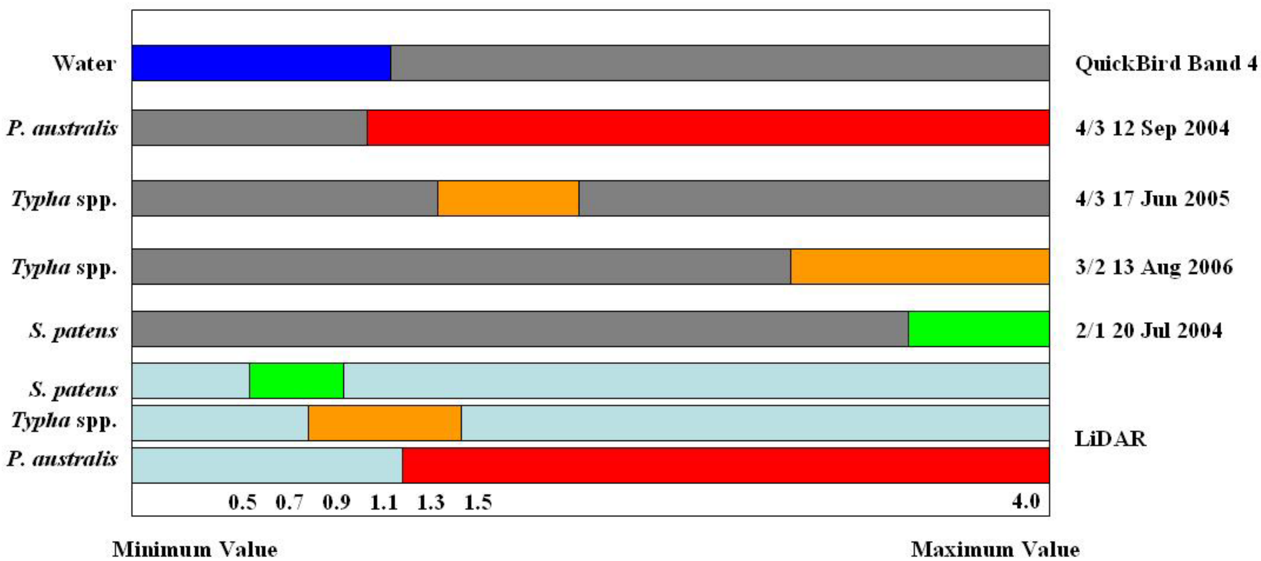

Fig. 6. Thresholds used for knowledge-based rules implemented in eCognition for the classification of image objects. Each bar corresponds to one rule that was applied to an image used to define each class.

Table 2. Frequency of correct matches for all map label categories based on two fuzzy operator choices: best choice, MAX (M) where linguistic level = 5 and acceptable choice RIGHT (R), with a linguistic level ≥ 3. The overall accuracy of all map labels, *i.e.*, the entire map, is given as the total. Area weights were determined by the contributing areal proportion of the map label categories.

		Technical Evaluation of Matches						
Map Label	Sites	MAX (M)		RIGHT(R)		Improvement (R-M)		Area Weights
Phragmites	68	66	(97.1%)	66	(97.1%)	0	(0.0%)	0.24130
Typha	157	99	(63.1%)	119	(75.8%)	20	(12.7%)	0.35783
S. patens	90	72	(80.0%)	83	(92.2%)	11	(12.2%)	0.21994
Other/Mix	64	46	(71.9%)	64	(100.0%)	18	(28.1%)	0.18093
Total	379	283	(74.7%)	332	(87.6%)	49	(12.4%)	1
Weighted Total			(76.5%)		(88.8%)		(12.3%)	

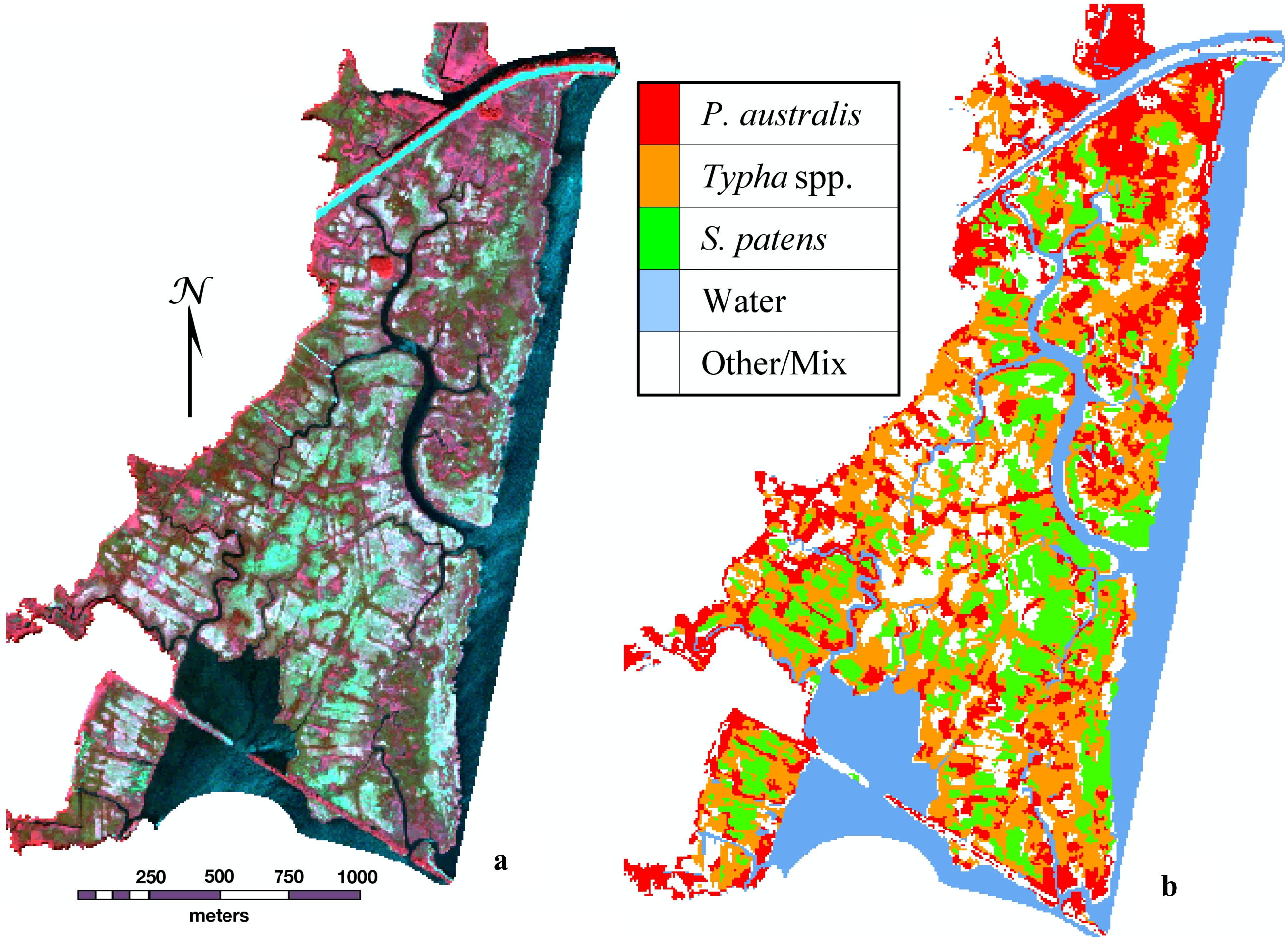

Fig. 7. (a) July 20, 2004 QuickBird 4-2-1 image. (b) Classification result.

4. DISCUSSION

4.1 Spectral Phenology

The spectral characteristics of vegetation are due to leaf pigments, plant structure (biomass and canopy architecture and cover) and plant health throughout the phenological cycle. Much of the spectral variability in the field data can be attributed to expected increases in plant pigments and biomass during the green up phase of plant growth, the decline of these variables and the increased contribution of background materials during senescence. The magnitude and rate of these changes is found to differ in individual species allowing their spectral discrimination at specific times during the growing season. The variability observed in individual reflectance spectra measured in the field was replicated when these spectra were resampled to QuickBird bands. Simple spectral indices were sufficient to distinguish the three dominant plant communities within a mosaic of other vegetation in Ragged Rock Creek Marsh.

Phragmites and *Typha* spp., which often occur as monocultures ≥ 2 meters high, had higher NDVI and NIR/red values throughout the growing season than the low-growing *S. patens*. NIR index values peaked for *Typha* spp. in the mid-late June, corresponding to field observations of peak plant heights of ≥ 2 meters, full development of flowers and wholly green leaves. *Phragmites* displayed peak NIR index values in mid-August to early September corresponding to peak plant heights of ≥ 3 meters and the development of flowers. Moreover, by late August, *Typha* spp. had senesced resulting in a reduction in green biomass and likely an increase in the contribution of background materials (wrack, soil) to its spectrum.

The green/blue ratio of *S. patens* was dramatically higher than that of *Phragmites* or *Typha* spp. from mid-June through late August, likely due to inherent differences in the amount of chlorophyll *b* and carotenoids in these species, both of which absorb in the blue portion of the spectrum. The peak in the green/blue index for *S. patens* in mid-July corresponds to maximum pigment concentration at this time of year.

The field data generated the following set of spectral rules that may be applicable to the discrimination of *Phragmites*, *Typha* spp. and *S. patens* communities: 1) *Phragmites* is best distinguished by its high NIR response late in the growing season likely due to its high biomass especially with respect to the other species, 2) *Typha* spp. is best distinguished by high red/green response in August due to senescence, and 3) *S. patens* is best distinguished by a unique green/blue ratio throughout the growing season attributed to pigments. The field data predict that seasonal spectral behavior should be evident within actual QuickBird data. To test this, we identified the image segments in eight QuickBird images containing the sites where the field point spectra were measured in 2005 and 2006. Average band values for all pixels within each segment were ratioed and plotted in Figure 4e-h. In the QuickBird data, *Phragmites* uniquely displayed high NDVI and NIR/red values late in the growing season (Fig. 4e,f), and *S. patens* had a relatively high green/blue values throughout the growing season (Fig. 4g). The red/green values for *Typha* (Fig. 4d) are greater than and separable from *Phragmites* throughout the growing season, but overlapped with *S. patens*. Thus, simple indices in four-band data such as QuickBird were adequate to measure and distinguish remotely the spectral characteristics of these species over the growing season.

The values of the QuickBird data spectral ratios for the field targets over the growing season follow the patterns established in the field data. As the QuickBird data were collected at various times of day and tidal stage, this suggests that the canopy spectra at the satellite level was dominated by vegetation, and the contribution of variable background elements like water and shade was minimal. The field targets were selected because they are monocultures with high areal density, so we expected little to no contribution of understory species in these data. Understory species may become an important part of the canopy spectrum in less dense stands, which may reduce classification accuracy. The agreement between field and satellite data supports the use of field spectra for the training of image classifiers.

The phenological trends seen here can vary as a function of plant vigor, which may depend on changes in salinity, climate, predation or disturbance. Corrections for interannual and regional changes in these factors must therefore be performed when attempting to interpret classification results or select dates to maximize interspecies spectral discrimination. However, the spectral trends noted here may have broader spatial and temporal application. We emphasize that in this study, the phenological behavior of the spectral indices is consistent over three years at two separate areas in both the field and satellite data of Ragged Rock Creek marsh. Furthermore, other studies show similar spectral behavior of wetland plant species. The late season peak in NIR reflectance we observed in our data for *Phragmites* is also noted for this species in VNIR field spectra measured in the New Jersey Meadowlands [14, 15] and in the Yangtze Estuary [16]. *Phragmites* is also found to be most spectrally separable from *Typha* spp. in field VNIR spectra measured in the Hudson River Estuary in late August [17]. These studies suggest that the spectral variability utilized here may be applied to other areas, particularly if guided by any ecological assessment of local growth habits of marsh species locally.

4.2 Classification

The object-oriented classification rules based on occurrence of a single species yielded the highest MAX accuracies as expected. This approach was the most useful for discriminating *Phragmites*, which occurred most often as monotypic stands. Yet, the marsh mosaic also included another, and perhaps more typical scenario, where several species are admixed in varying amounts. Treating the validation points in this study with linguistic values, fuzzy accuracy assessment and the RIGHT accuracy measure enabled an arguably more realistic interpretation of vegetation stands with co-dominant or transitional species typical of many marshes. Similar improvements in accuracy between MAX and RIGHT measures have been noted for the mapping of marsh vegetation using QuickBird imagery with eCognition™ [18].

Using the RIGHT accuracy measure improved results for *S. patens*, which we suggest resulted from its distribution as understory in many of the validation quadrats. In these situations, the spectral signature of *S. patens* contributes to the signal even if taller species dominate the LiDAR first return (canopy) data. Also, *S. patens* was most often confused for bare ground/flotsam/wrack, which are all low-lying and spectrally bright and for other low growing species such as blackgrass (*Juncus gerardii*), bentgrass (*Agrostis stolonifera*) and switchgrass (*Panicum virgatum*).

Typha spp., the most overmapped class, was confused with *Phragmites* and a number of other species. Examination of the validation data shows that the classification misidentified many points where *Typha* spp. was recorded in low abundance. These points contain *Typha* spp., which occasionally has a diffuse clonal growth habit, within a mix of species of various heights, spectral signatures and densities. Many of these species, like *Phragmites*, are observed to occur at similar heights (approximately 1 – 2 m) to *Typha* spp. during the middle part of the growing season, including sedges (*Schenoplectus* species) and bulrushes (*Bolboschoenus* species). The wide range of species that are confused with *Typha* spp. is likely exacerbated by its lack of an extreme, defining spectral or height rule. In contrast, both *Phragmites* and *S. patens* have extremes in the LiDAR data (tallest and shortest, respectively) and have one band ratio that is quite distinct (late season NIR/red and mid-season green/blue, respectively). The fact that *Typha* spp. covers the most area of the marsh may also increase the potential for commission error.

Elevation information, such as that derived from LiDAR, is an important feature of natural vegetation classification. *Phragmites* was observed to be approximately 1 m taller than the next tallest species in late summer. This characteristic distinguishes *Phragmites* from *Typha* spp. and *S. patens* in the LiDAR data, likely contributing to the success of its classification. While it is possible that the use of LiDAR as a sole discriminant could identify a large proportion of *Phragmites* occurrences, the spectral characteristics are likely necessary to distinguish between *Phragmites* and *Typha* spp. because there is considerable overlap in the height data of these species (Figs. 5 and 6).

4.3 Implications

The canopy spectral and structural characteristics of *Phragmites*, *Typha* spp. and *S. patens* vary as a function of plant phenology in both field collected and QuickBird images. The plant communities were found to be separable spectrally in four-band data and thus we predict that other systems such as ALI or IKONOS could be used for marsh plant classification, obviating the need for more expensive hyperspectral airborne data. The spatial resolution of QuickBird images approximates the patch size of the mapped plant species in Ragged Rock Creek marsh, which likely contributes to the success of the classification. We would expect classification accuracy to degrade with lower spatial resolution data (*e.g.* Landsat) as has been noted in other attempts to classify salt marsh vegetation [5].

The seasonal variations in spectral behavior make clear the necessity of multi-temporal imagery for mapping multiple species on a complex tidal marsh. Our study demonstrates that field observations at a limited number of reference sites were sufficient for classification. The spectral and structural data predicted times during the growing season when each species was best discriminated. With this knowledge, a single date of imagery could be used to map adequately a single species. For example, in Ragged Rock Creek marsh, the high NIR response and height of *Phragmites* in the autumn distinguishes it uniquely among a mosaic of plant species typical of a brackish marsh. Natural resource land managers seeking to monitor *Phragmites* in this region could utilize single date color infrared images, four-band satellite data and/or LiDAR during late August to early September for classification. Classification could be accomplished at other marshes with field observations at a limited number of reference sites.

5. CONCLUSION

This study presents a new technique for the classification of major marsh plant species within a complex, heterogeneous tidal marsh using multitemporal QuickBird images, field reflectance spectra and LiDAR height information. Analyses of the phenological variation of spectral and structural characteristics of marsh species measured in the field throughout the growing season were necessary to select the best dates to discriminate *Phragmites*, *Typha* spp. and *S. patens*. These three species are spectrally distinguishable at particular times of year likely due to differences in biomass and pigments and the rate at which these change throughout the growing season. These differences are recognizable both in high-resolution field spectra, in the spectra when degraded to spectral resolution typical of four-band multispectral sensors and in QuickBird images of the field sites.

Rules based on the spectral variability of species throughout the growing season were used to direct the classification of multitemporal QuickBird images. Classification accuracies for *Phragmites* were high due to the uniquely high NIR reflectance and height of this dense monoculture in the early fall. Mapping accuracies were best represented for all species by using a fuzzy accuracy assessment, which accommodates the complex mosaic of dominant and mixed plant communities of Ragged Rock Creek marsh. For classification, the spectral data supplements the LiDAR data as it may include contributions from understory species like *S. patens*.

The results of this study demonstrate the utility of remote sensing to map certain types of marsh vegetation. Although multitemporal image data were utilized for the classification in this study, the phenological variations recognized here can be utilized for judicious selection and analysis of single date, four band satellite or aerial image data having the same wavebands of coastal marshes along Long Island Sound. Such data are likely to be useful to coastal managers and may greatly facilitate the identification and inventory of marsh species.

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