Remotely Sensed Estimates of Vegetation Structural Characteristics in Restored Wetlands, Southern California

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Abstract

Traditional field sampling approaches for ecological studies of restored habitat can only cover small areas in detail, can be time consuming, and are often invasive and destructive. Spatially extensive and non-invasive remotely sensed data can make field sampling more focused and efficient. The objective of this work was to investigate the feasibility and accuracy of hand-held and airborne remotely sensed data to estimate vegetation structural parameters for an indicator plant species in a restored wetland. High spatial resolution, digital, multispectral camera images were captured from an aircraft over Sweetwater Marsh (San Diego County, California) during each growing season between 1992-1996. Field data were collected concurrently, which included plant heights, proportional ground cover and canopy architecture type, and spectral radiometer measurements. Spartina foliosa *(Pacific cordgrass) is the indicator species for the restoration monitoring. A conceptual model summarizing the controls on the spectral reflectance properties of Pacific cordgrass was established. Empirical models were developed relating the stem length, density, and canopy architecture of cordgrass to normalized-difference-vegetation-index values. The most promising results were obtained from empirical estimates of total ground cover using image data that had been stratified into high, middle, and low marsh zones. As part of on-going restoration monitoring activities, this model is being used to provide maps of estimated vegetation cover.*

Introduction

Data on the type of vegetation cover and its structural properties in a restored wetland are required for adaptive management and to provide evidence that a restoration effort has met certain goals. Hence, monitoring and management applications require maps of vegetation composition and structural properties, such as horizontal cover, biomass, and density. Traditional field sampling approaches for obtaining ecological data in restored wetlands are limited in extent and/or density of measurements and are often invasive and destructive. To produce accurate and useful data or maps of vegetation composition or percent cover requires an approach that is capable of providing rapid, contiguous coverage of a large area. Remotely sensed data from airborne or spaceborne sensors provide a spatially extensive and non-invasive means to produce maps of surface cover types and their biophysical properties. These data can be processed and analyzed to yield maps for restoration monitoring and to make field sampling more focused and efficient.

Remotely sensed data in the form of aerial photographs and images from satellite and airborne platforms have been applied extensively to inventory, monitoring, and research problems in natural coastal wetlands along the Atlantic and Gulf coasts of the United States (Gross *et al.*, 1989; Dobson *et al.*, 1995). Two main divisions are evident in these applications of remotely sensed data, either as a tool for delineating wetlands and mapping their internal composition, or for estimating biophysical and biogeochemical properties. With the exception of extensive evaluation projects conducted by Zhang *et al.* (1997) in San Pablo Bay, and in San Diego Bay (Phinn *et al.*, 1996), and coastal change analysis projects in the Columbia River Estuary (Dobson *et al.*, 1995) and San Francisco Bay/Elkhorn Slough (Harris, 1994), there has been very limited application of remotely sensed data to Pacific Coast wetlands and no applications for monitoring restored wetland environments. This may be attributed to the small size of restored wetlands and lack of baseline remotely sensed data for monitoring these environments.

Any application of remotely sensed data to a monitoring problem should be based on an established link between the information required and its measurement in remotely sensed data. Hence, the objective of this work was to investigate the feasibility and accuracy of hand-held and airborne remotely sensed data for estimating the structural parameters of an indicator plant species, *Spartina foliosa* (Pacific cordgrass), in a restored wetland.

The Sweetwater Marsh National Wildlife Reserve in San Diego County was the principal study site for this work. This 110-hectare reserve consists of natural and restored saltmarshes. Salt marsh construction projects have been underway in this wetland since 1987 for the Connector Marshes and since 1991 for Marisma de Nación (Figure 1). Mitigation assessment criteria for each wetland require the restored site to contain at least seven breeding home ranges for the light-footed clapper rail (*Rallus longirostiris levipes*), a California state listed endangered bird species. Requirements for vegetation composition and structure for each clapper rail home range have been established from extensive field work in natural habitat

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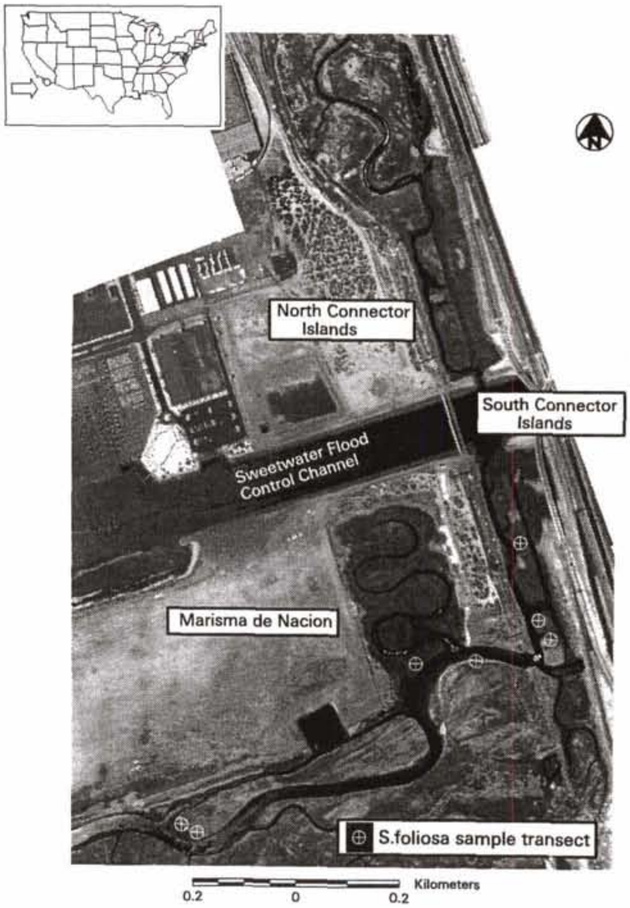

Figure 1. ADAR-5500 NIR band mosaic of Sweetwater National Wildlife Refuge. The refuge is located near San Diego and National City, California, and is adjacent to San Diego Bay. The North and South Connector Islands and Marisma de Nación areas are constructed marshes.

(Zedler, 1993). Specifically, each home range must be at least 0.8 hectares in extent, with 15 percent of that area being composed of high marsh vegetation and 15 percent by low marsh vegetation. Within the low marsh, areas of Pacific cordgrass, in which the clapper rail builds its nest, patches should be 90 to 100 m² in size, with an overall plant density of 100 stems per m², and stem lengths between 60 cm and 80 cm. Horizontal cover requirements were defined for the low (> 90 percent) and middle (> 70 percent) marsh zones. Due to the potential damage and disturbance associated with field surveys for mapping vegetation composition and identifying potential home ranges, remote sensing techniques were examined as alternative data sources.

Data and Methods

Remotely sensed data for this project consisted of low-level spectral radiometer data from hand-held radiometers and multispectral image data from a digital camera system. Differentially corrected Global Positioning System (GPS) surveys and measurements of structural properties of vegetation were conducted in conjunction with the hand-held measurements and at the same time as overflights to acquire multispectral digital image data of the site. Data sets obtained from these exercises were analyzed to determine the strength of several relationships: (1) controls of *S. foliosa* stem length and density on its spectral reflectance, (2) general controls of *S. foliosa* canopy architecture on its spectral reflectance, and (3) estimates of horizontal projected foliar cover from multispectral digital camera data.

Data

Ground-based radiometric and biophysical data were obtained from seven transects in pure stands of *S. foliosa*, 12 m to 78 m in length, sampled at 3-m intervals using a 0.1-m² circular sampling plot. This sampling resulted in 108 plots of monospecific stands of *S. foliosa*. The transects were sampled on a monthly basis between April and October for the period 1992 to 1995. Three of the *S. foliosa* transects are in natural sites (transects A, F, and G) and four in restored areas (transects B, C, D, and E) (Figure 1). Hand-held radiometer data were obtained for each plot in blue (450nm to 520nm), green (520nm to 600nm), red (630nm to 690nm), and near-infrared (760nm to 900nm) wave-bands using an Exotech 100 radiometer. The radiometer was held 1.1 m vertically above the plant canopy. At this height with a 15° field of view, the instrument was recording data from a circular area on the canopy with a diameter of approximately 30 cm. Data were acquired at these scales to coincide with existing and on-going field sampling of *S. foliosa* structural parameters conducted for related projects that had previously established scales of variability in *S. foliosa* and suitable sampling strategies (Zedler, 1993). Three sample radiometer measurements were made in each of the four radiometer bands at each sample point using a data logger attached to the radiometer. These data were calibrated using measurements from a Spectralon® calibration panel (taken at regular intervals during sampling) by using the Refl5x program provided by the United States Department of Agriculture, Agricultural Research Service Water Conservation Laboratory (Carney *et al.*, 1986). Refl5x was run utilizing the gain and offset coefficients provided by Exotech to calculate an average at-sensor spectral radiance from the three measurements at each sample point. The closest calibration panel measurement in time was then used to calculate an average at-sensor spectral reflectance value for each sample plot. Table 1 lists the vegetation and marsh cover types for Sweetwater Marsh.

To ensure maximum insolation and to minimize water coverage of plants (i.e., by tidal inundation), radiometer and spectrometer measurements were taken between 1000 and 1400 hours solar time and at low tide. This was also the optimum time to record spectra from the range of canopy

TABLE 1. VEGETATION AND MARSH COVER TYPES FOR SWEETWATER MARSH

Vegetation Cover Type	Marsh Cover Type
Channels and standing water	channels and standing water
moist substrate	moist substrate
dense Spartina foliosa	low (dense Spartina foliosa)
– sparse Spartina foliosa	low
– Spartina foliosa, Batis maritima, Jaumea carnosa	low
– Spartina foliosa, Salicornia bigelovii	low
– Salicornia bigelovii	low
– Salicornia bigelovii, Batis maritima, Spartina foliosa	low-middle
– Spartina foliosa, Salicornia virginica	low-middle
– Salicornia bigelovii, Batis maritima, Jaumea carnosa	low-middle
Salicornia virginica, Salicornia bigelovii	middle
Salicornia virginica, Batis maritima, Salicornia subterminalis	middle-high
high – bare and dry substrate	high bare-dry
high marsh mixture : Distichlis spicata, Frankenia grandifolia, Salicornia subterminalis, Monanthchloe littoralis	high

architecture types present in the marsh (broadleaf, gramineous, and leafless). Previously, researchers examining canopy characteristics in similar environments have determined that differences in vegetation spectra due to structure, condition, and radiative transfer characteristics were best determined at high sun angles (Bartlett *et al.*, 1988; Gross *et al.*, 1989; Walter Shea *et al.*, 1992).

Ground-based measurements of vegetation structural properties were made for *S. foliosa* plots and transects immediately before or after image acquisition overflights and hand-held radiometer data collection. Measurements of *S. foliosa* morphology were made within a 0.1-m^2 circular plot corresponding to the area canopy radiometric measurements were taken from. For *S. foliosa*, live and dead stem lengths were counted and measured along with canopy architecture (flatness), presence of standing water, and algae. Values for the flatness scale were based on the observed deviation of dominant canopy orientation, estimated from a vertically orientated measuring pole placed at the base of each sample plot: Class 1 — vertical (90°); Class 2 — between 90° and 60°; Class 3 — between 60° and 30°; and Class 4 — horizontal (30° to 0°).

ADAR (Airborne Data Acquisition and Registration) high resolution, digital, multispectral image data sets (Stow *et al.*, 1996) were acquired by Positive Systems Inc. over the entire Sweetwater Marsh National Wildlife Reserve in 1992 (July, September), 1993 (April, August, October), 1994 (April, July, September), 1995 (June, September), and 1996 (July). Images were acquired with a ground resolution element of 0.75 m in the blue (424 to 494 nm), green (521 to 599 nm), red (620 to 694 nm), and near-infrared (NIR, 813 to 1001 nm) wave-bands. Image acquisition took place under clear sky conditions and at low tide to minimize tidal inundation effects.

Horizontal projective cover was assessed as the percentage of a unit area of ground covered by green vegetation when viewed from a NADIR perspective. Field data were collected for all marsh cover types in a field program separate from the *S. foliosa* measurements (discussed previously) during August 1995 and July 1996 by personnel from the Pacific Estuarine Research Laboratory (PERL). A total of 28 transects were sampled on both dates in the North and South Connector Islands (Figure 1), with eight in low marsh, 12 in middle marsh, and eight in high marsh. The transects were 4.5 m in length and contained six plots sampled using a 0.75-m by 0.75-m plastic frame to approximate the dimensions of the ADAR ground resolution elements. The plastic frame contained five equally spaced strings on either side of the frame to produce 25 sample points. Horizontal projective cover was recorded by first placing the sampling frame adjacent to a tape marking the transect line at its start point. An observer positioned the sampling frame above the canopy layer and a second observer then viewed the sampling frame from above to determine the number of string intersection points that were directly above green vegetation. Cover was then recorded as a fraction of the 25 possible "hits" produced at intersection points of the five-string grid. The type of vegetation occurring at each "hit" was also recorded. After completing one sample frame, the plastic grid was flipped over in the direction of the transect, allowing a total of six 0.75-m by 0.75-m samples to be made along each 4.5-m transect line.

Differential GPS equipment was used to survey all the vegetation sample plots and transect locations with a high degree of horizontal and vertical precision (0.03 m and 0.05 m, respectively). Survey points were converted to a vector (point data) coverage in the coordinate system that conformed to the georeferenced ADAR image data. This enabled the GPS survey points for each transect endpoint to be displayed and analyzed in correspondence with the ADAR image data and vegetation and marsh cover-type classification maps derived from the ADAR data.

Methods

S. foliosa *Stem Length and Density Controls on Spectral Reflectance*

Seven sampling transects (108 plots) were utilized to examine relationships between spectral vegetation indices (SVIs) and *S. foliosa* total stem length (TSL) during 1992-1993 in both restored and natural and restored sections of Sweetwater Marsh (Van Mouwerik, 1993). Individual plots were also pooled by transects and by stem length to test for improvements in the strength of relationships. Analysis of Variance (ANOVA) was applied to groupings of short, medium, tall, and sparse and dense cordgrass to determine if SVIs were sensitive to differences in structural characteristics.

S. foliosa *Canopy Architecture and Reflectance Model*

Canopy architecture controls on *S. foliosa* reflectance values were examined from two sources: (1) field observations made during a subset of the field programs (Fall 1992–Summer 1993), and (2) literature describing the anatomy and growth forms of *S. foliosa* (e.g., Kasapligil, 1974; Macdonald, 1988; Zedler, 1993). We only examined the effects of different canopy architecture types (CATs) and assumed that other spectral reflectance control factors (e.g., sensor look angle and solar angle) were constant.

Radiometric samples for each field program were categorized into one of four CATs. An ANOVA utilizing the F-test, Fisher's protected LSD, and Scheffe's tests was conducted to determine if there were significant differences between the mean SVI values of different CATs for each season. In more erectophile canopies, substrate characteristics are expected to control spectral reflectance. In more planophile canopies, canopy greenness, and health are considered the most significant controls (Bartlett *et al.*, 1988; Walter-Shea *et al.*, 1992).

A framework was developed to relate the results from previous research that examined factors controlling *S. foliosa* SVI variation. This involved the design of a conceptual model that identified all of the factors affecting *S. foliosa* spectral reflectance. Once established, the model enabled those factors to be identified that had not been examined in the field or for which there was no relevant research literature.

Estimates of Horizontal Cover Using ADAR Data

Multiple regression analyses were applied to relate percent ground-cover measured in the field along transects to green, red, and NIR reflectance and NDVI values of corresponding pixels within the 10 June 1995 and 28 July 1996 ADAR images. To enable identification of the ADAR bands that would be most useful in estimating cover, multiple combinations of the green, red, and NIR bands were examined. Due to the control that differences in the vertical and horizontal structure (internal architecture or form) of wetland plants in different elevation assemblages has on their reflectance characteristics, previous research recommended stratification of vegetation data into relevant units to maximize the accuracy of regression models for estimating structural parameters (Hardisky *et al.*, 1983b; Gross *et al.*, 1989). Hence, the field and ADAR data were stratified into low (n = 48), middle (n = 72), and high marsh (n = 48) groups and regressions were performed on these individual groups or strata.

In order to locate ADAR pixels that most closely corresponded to field sampled locations, GPS measurements of transect end-markers were displayed on the ADAR image mosaics for 10 June 1995 and 28 July 1996. They were magnified to the point where individual pixels could be discerned. Once the pixels corresponding to each field plot along the transect were identified, digital numbers (DN) and reflectance values were extracted and entered in a spread-sheet along with the cover data for each plot. Both the pixel DN/reflectance and cover data sets for each marsh cover type were examined to ensure they met the processing assumptions of regression analysis. These assumptions included the following: (1) data exhibit linear relationships, (2) expected estimation error values have a mean of zero, (3) estimation errors have same variance and are not correlated, (4) input data values are independent, and (5) number of observations is greater than number of independent variables.

Multiple regression models were applied to all possible combinations of the ADAR image bands (green, red, NIR, and NDVI) and the corresponding field-based cover measure. The regression model associated with the combination of image bands that produced the highest significant relationship with field sampled cover data was selected for the low, middle, and high data sets to apply to the rest of the image data. The transect data served as the calibration for estimating horizontal projective cover in the remaining low, middle, and high marsh areas of the image. An existing delineation of marsh-cover types based on the images used in this work was available and was used to stratify low, middle, and high marsh pixels (Table 1). Each regression model was then applied to the relevant marsh-cover subset using the Erdas Imagine 8.2 Spatial Modeling utility to produce an image where brightness values extend from 0 (no cover) to 25 (100 percent cover). Estimated cover values were then validated with field sampled data to provide a root-mean-square error estimate. Detailed maps were provided to biologists, with low, middle, and high marsh cover estimates, indicating areas in compliance and not in compliance with restoration criteria.

Results and Discussion

S. foliosa Stem Length and Density Controls on Spectral Reflectance

Results indicated that, for all plots, live total stem length explained a significant and higher proportion of variance of NDVI and simple ratio derived from hand-held spectral radiometer measurements than any other combination of SVI and vegetation property (Figure 2 and Van Mouwerik (1993)). SVIs grouped by marsh type (natural versus constructed), by age within the constructed marsh (three versus eight years), and by live TSL (short versus tall), all had significantly different mean values. No relationship was found between SVIs derived from ADAR images and stem length or density.

TABLE 2. *S. FOLIOSA* CANOPY ARCHITECTURE TYPES

Canopy Architecture Type	Canopy form and angular distribution
Type I	vertical 90°
Type II	slightly flattened 90° – 60°
Type III	moderately flattened 60° – 30°
Type IV	flat 30° – 0°

S. foliosa Canopy Architecture and Reflectance Relationships

The control of *S. foliosa* canopy architecture types on its spectral reflectance properties was established for four different canopy architecture types (CATs). Table 2 describes the CATs that represent the broad range of *S. foliosa* canopy forms and leaf angle distributions observed in the Sweetwater Marsh transects during each stage of the growing season. Variations in canopy architecture result from one or more of the following: phenology, growth form, local (plant level) environmental conditions (tides, winds), and disturbance (trampling, herbivory, parasitic insects, and nutrient/salinity stresses).

An erectophile canopy is predominant for *S. foliosa* stands during earlier stages of their green-up phase (spring). Such stands contain new stems and dead remnants from previous years. Spectral reflectance measured when this CAT dominates is likely to be influenced strongly by substrate characteristics. The other remaining CATs represent progressive flattening of the *S. foliosa* canopy associated with its annual growth cycle or in response to shorter duration environmental disturbances. Initially, these structural changes reduce substrate contributions to remotely sensed reflectance and result in SVIs becoming more sensitive to the proportion of live and dead canopy biomass (Figure 3). Towards the end of sum-

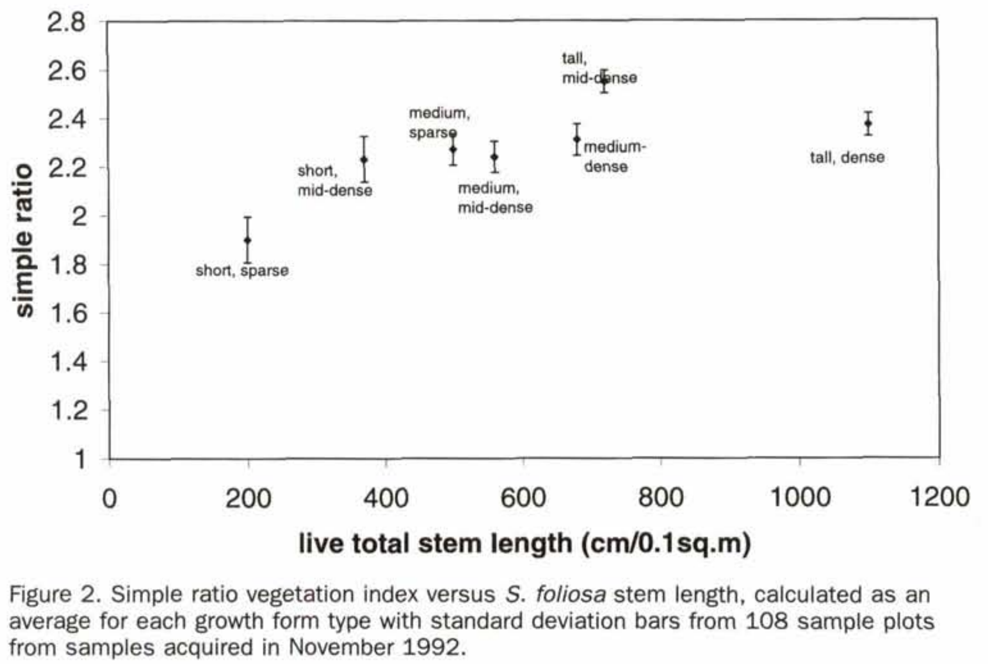

Figure 2. Simple ratio vegetation index versus *S. foliosa* stem length, calculated as an average for each growth form type with standard deviation bars from 108 sample plots from samples acquired in November 1992.

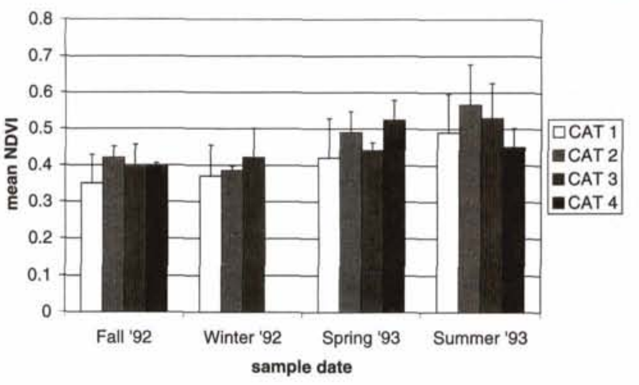

Figure 3. Mean NDVI by canopy architecture type (CAT) in each season, calculated from 108 sample plots.

mer significant changes also begin to occur in the spectral characteristics of *S. foliosa* canopy due to inflorescence and then senescence causing the canopy to "brown off." Changes to a flat CAT are usually permanent, due to disturbance, flattening by tidal overflow, and debris or senescence.

Spectral vegetation indices for the different *S. foliosa* canopy architecture types exhibited constant differences during each sample period. Therefore, specific consideration should be given to the canopy architecture type when examining the spectral response of *S. foliosa* and relating it to biophysical parameters. This may be achieved by recording parameters related to the plant's canopy architectural characteristics (e.g., horizontally and vertically project leaf-area, leaf-angle distribution) and examining their interaction in a suitable radiation transfer model.

The cause, seasonal occurrence, and effect on the plants' spectral reflectance control factors of each CAT were established and used to estimate their spectral response. Statistically significant differences were then observed at each stage in the growing season between the mean SVI for plots in each CAT. Between CATs I and II, similar variations in each season's SVI values were attributed to changes in the structural aspect of the canopy from erectophile to planophile, increasing the amount of biomass intercepting and reflecting radiation. As the canopy types became more planophile (Types II to III), the mean SVI values decreased in response to physiological changes in the canopy associated with progressive flattening affecting the canopy's radiative transfer characteristics, and increased exposure of stems as opposed to leaves.

Canopy architecture appears as one of the main influences on the relative contribution of the spectral reflectance control factors in *S. foliosa*. For example, reflectance from erectophile canopies is influenced by substrate characteristics. In contrast, vegetation health and live/dead proportion are more dominant controls of planophile canopy reflectance. Results from the regression analyses of SVI values with live-stem lengths for different CATs confirm earlier findings that structural aspects of *S. foliosa* only contribute partly to SVI variation, while *S. foliosa* radiative transfer characteristics may be the more dominant controls as suggested by Bartlett *et al.* (1988; 1990) for *Spartina alterniflora*.

A descriptive, conceptual model was constructed to summarize our findings (Figure 4). In addition to the results discussed here, the model is based on previous research on *S. foliosa* by Van Mouwerik (1993), on *S. alterniflora* by Hardisky *et al.* (1983a; 1983b), Bartlett *et al.* (1988), Morris (1989), and Gross *et al.* (1989); and on the spectral properties of grasses in general (Norman *et al.*, 1985; Sellers, 1985; Walter-Shea *et al.*, 1992). Each component of the model identifies variables and inter-relationships that have been established from empirical studies to control (1) the amount of direct and diffuse electromagnetic radiation (EMR) incident on canopy, understory, and substrate components of an *S. foliosa* stand; (2) the amount of EMR absorbed, transmitted, and reflected from components of an *S. foliosa* stand; and (3) the amount of EMR reaching the radiometer from an *S. foliosa* stand.

Each component of the model was utilized to determine why the SVI stem-length relationship for *S. foliosa* was not stable. Field sampling of 65 *S. foliosa* plots using a hand-held radiometer in August and September 1994 was accompanied by measurements of stem lengths, leaf numbers, and leaf lengths in each sample plot. Leaf length and stem length were found to be linearly related up to a stem length of 40

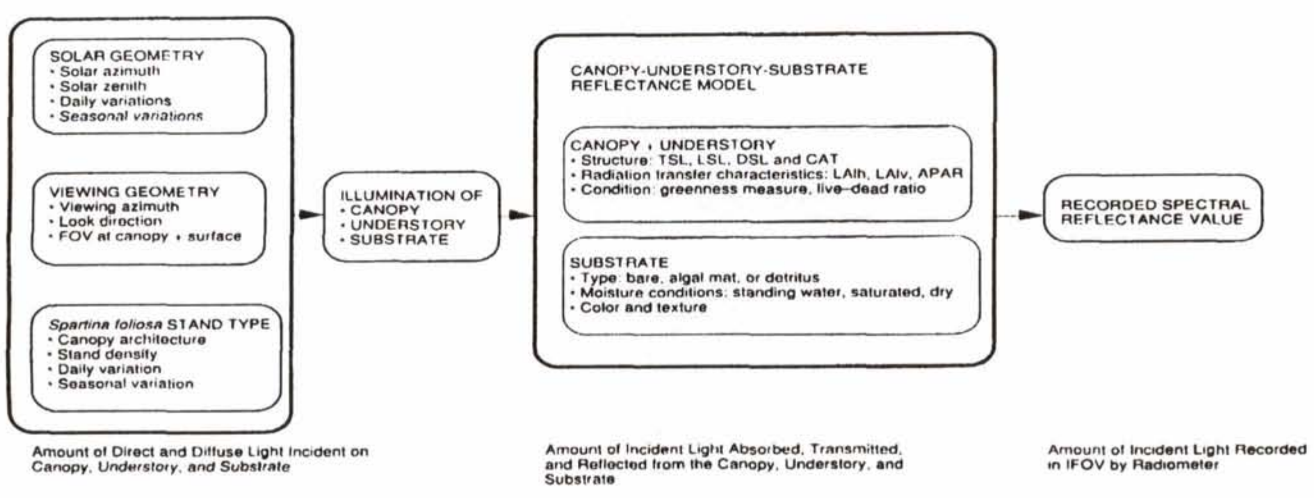

Figure 4. *Spartina foliosa* spectral reflectance model. The model is based on previous research on *S. foliosa* by Van Mouwerik (1993); *S. alterniflora* by Hardisky *et al.* (1983a; 1983b), Bartlett *et al.* (1988), Morris (1989), Gross *et al.* (1989); and on the spectral properties of grasses in general (Norman *et al.*, 1985; Sellers, 1985; Walter-Shea *et al.*, 1992).

VEGETATION COVER ESTIMATE FOR LOW MARSH AREAS
SWEETWATER MARSH RESTORATION SITE

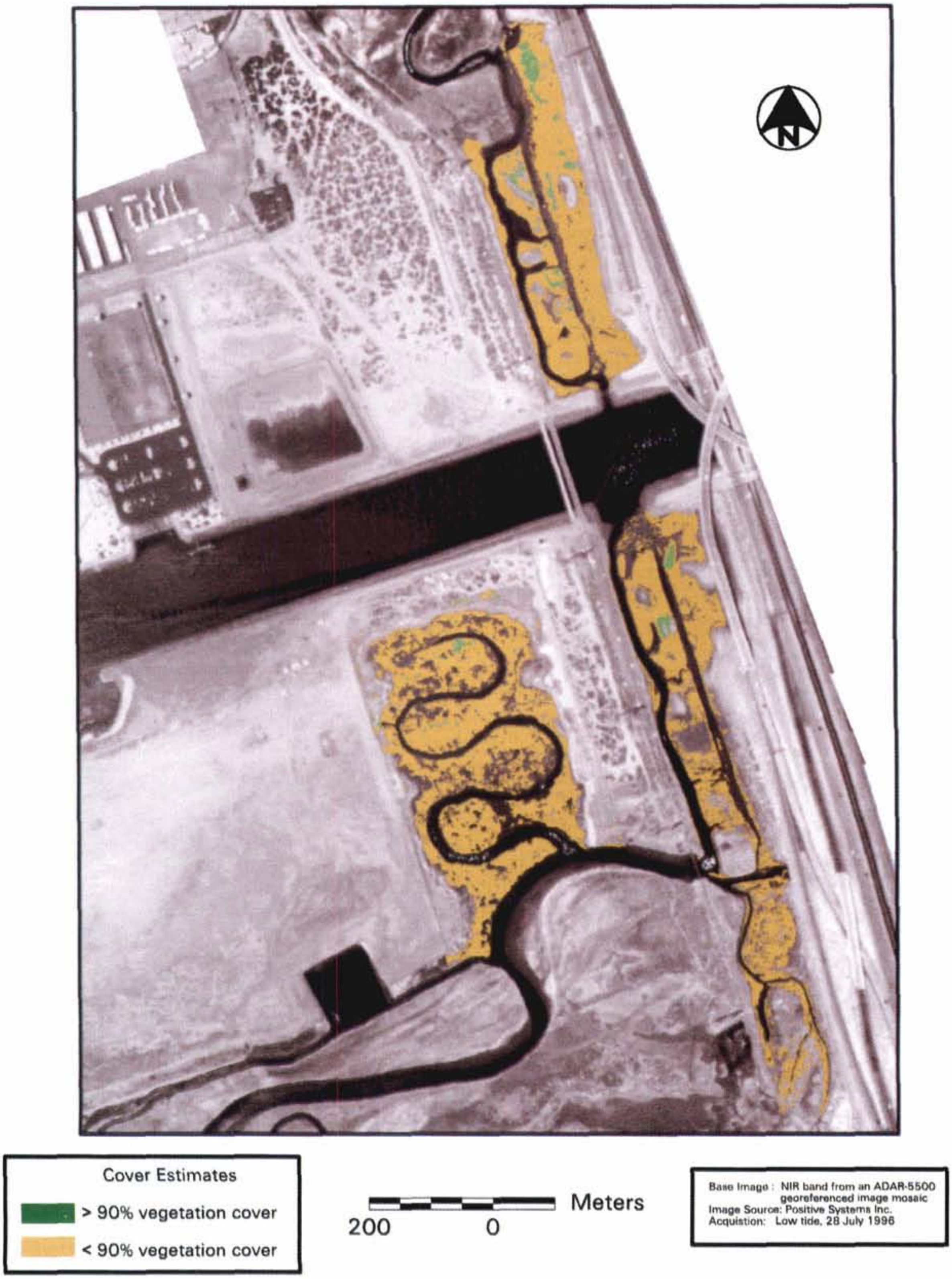

Plate 1. Map of estimated percentage plant cover above and below the 90 percent threshold for low marsh habitat zones based on ADAR 5500 data acquired on 10 June 1995.

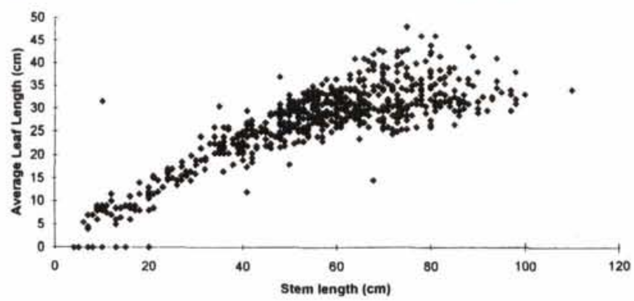

Figure 5. *Spartina foliosa* stem length and leaf length, Sweetwater Marsh, during August 1994 sampled from 65 plots (n = 264 plants).

cm. Beyond this height the leaf length and stem length relationship becomes non-linear and less coherent (Figure 5). For example, leaf and stem lengths are similar in the short and medium forms.

Figure 5 demonstrates that for the tall forms the stems continue to grow after the leaves reach a maximum length. The maximum leaf length was about 35 to 40 cm in the *S. foliosa* plants examined. These results provide a physical basis for the instability in *S. foliosa* SVI/TSL relationships derived by Van Mouwerik (1993). Hardisky *et al.* (1983a) noted that the relationships established between *S. alterniflora* SVI and its TSL were only significant for short form plants. Morris (1989), in producing plots of photosynthetically active radiation (PAR) attenuation in *S. alterniflora* canopies, also observed similar effects. Therefore, the canopy structure variables controlling spectral reflectance, i.e., leaf length (amount of green biomass), are only linearly related to stem length in short form plants (TSL < 40cm). Reliable and spatially continuous estimates for stem length values of *S. foliosa* are not likely to be derived from spectral radiometric data (hand-held or airborne imaging) and spectral vegetation indices for stands greater than 40 cm high.

Estimates of Horizontal Cover Using ADAR Data

Regression of ADAR derived spectral indices on percent ground cover for the low, middle, and high marsh plots (Table 3, Figure 6 and Plate 1) yielded high r^2 values for all band combinations, with the exception of the NIR band in high marsh areas. As vegetation type and structural differences between low, middle, and high marsh plants are considered the primary factors responsible for differences in their spectral reflectance, we applied a marsh-cover type map to stratify the ADAR image into low, middle, and high marsh cover types (Table 1). Once the stratification by marsh zone was complete, regression relationships for ADAR DN versus horizontal vegetation cover developed at marsh assemblage level were applied to those pixels corresponding to low, middle, and high marsh cover types.

Before one applies regression relationships to estimate total cover from ADAR digital numbers for each pixel in the wetland, several limitations should be recognized. First, the cover estimates made from 25 points within the 0.75- by 0.75-m sample grids used in the field appear to be too sparse at present to maximize the full potential of the information contained in ADAR data. This is indicated by field cover values reaching their peak, while ADAR SVI values continue to increase (Figure 6). Second, horizontal projective foliage cover is only one of the major factors identified as controlling spectral reflectance from wetland vegetation. The following factors should also be taken into account (e.g., by stratifying into elevational assemblages) to isolate and maximize cover estimations:

- percentage of leaf area in horizontal and vertical planes,
- amount of light penetrating the canopy,
- quantity and orientation of dead biomass, and
- amount of substrate exposed relative to vegetation.

TABLE 3. SUMMARY OF REGRESSION ANALYSIS RESULTS (R^2) BETWEEN ADAR IMAGE VALUES AND GROUND COVER MEASUREMENTS

Image Date	Green-Red-NIR	Red-NIR	NIR	NDVI
low marsh 6/95	0.51	0.51	0.49	0.48
low marsh 7/96	—	0.39	—	0.36
mid marsh 6/95	0.63	0.60	0.63	0.52
mid marsh 7/96	—	0.57	—	0.72
high marsh 6/95	0.73	0.72	−0.19	0.55
high marsh 7/96	—	0.74	—	0.55

Application of each inverted regression model to the pixels classified as low, middle, or high marsh types in the ADAR image from June and August yielded three separate image maps of horizontal projective cover estimates for each date. The root-mean-square error (RMSE) was derived for the estimated cover values corresponding to the pixels where the field transects were sampled in both the 1995 and 1996 images. Due to the fragile nature of the restoration site and in order to minimize the extent of intrusive work, all the points used to derive the regression relationship were utilized as validation pixels. The sample set for developing the regression models would have been inadequate if fewer sample points were retained and the remainder used to generate RMSE values. The RMSE for the June 1995 cover estimate image was 3.8 percent and for August 1996 was 4.9 percent. In both cases, the low and high marsh estimates were greater than 90 percent accurate, while the accuracy of the middle marsh was between 80 and 90 percent. The lower accuracy of the middle marsh estimates may be attributed to the inclusion of transitional low and high marsh pixels in this class, both of which have significantly different canopy structures. Due to the lack of "pure" or unique middle marsh canopy types, the regression model tended to overestimate cover in areas confused with low and high marsh.

To provide information useful for biologists and resource managers to assess the progress of the constructed saltmarsh at Sweetwater Marsh, all three cover estimate images were combined and overlaid on the ADAR false color composite (Plate 1). This image was used as a reference for locating areas with the highest and lowest cover in each marsh zone and was simplified to delimit areas with greater than 90 percent cover in the low marsh and greater than 70 percent in the middle marsh (Plate 1). Summary statistics on the horizontal cover in high, middle, and low marsh zones were then provided for specific polygons and for each potential clapper rail home range. These data complement statistics already provided from the image classification on the area occupied by each marsh cover type in the home ranges and were used to determine where intensive field sampling of species cover would be performed (Phinn *et al.*, 1996).

Conclusions

The results presented here indicate that several of the biophysical properties of coastal wetland vegetation in southern California can be estimated at an adequate level of precision and accuracy using high spatial resolution multispectral data from field radiometers and airborne digital cameras. Similar conclusions were reached for northern California saltmarshes by Zhang *et al.* (1997). Careful consideration of the time of day and season most suited to differentiating the wetland vegetation types was required. For one indicator species, *S.*

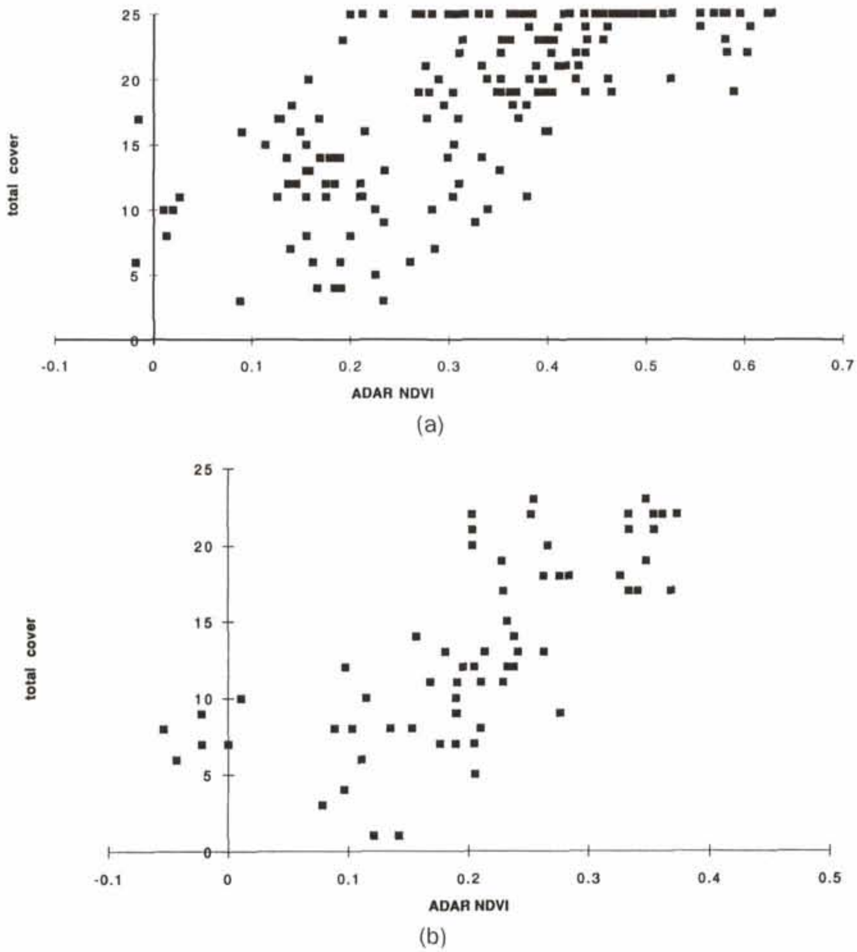

Figure 6. ADAR NDVI pixel values plotted against ground-based cover measurements from each pixel for all sample plots, (a) 1995 (n = 168) and (b) 1996 (n = 72).

foliosa, particular attention was paid to determining whether or not its structural properties could be estimated from hand-held or airborne remotely sensed data. Because the primary difference between zonal marsh vegetation types is structural, stratification of the wetland on this basis enables models to be applied for accurately estimating structural parameters controlling spectral reflectance.

Assessment of ground sample data and spectral reflectance measurements of *S. foliosa* enabled identification of *S. foliosa* structure and condition variables that control its spectral radiometric properties. Estimates of total stem length of *S. foliosa* plots that are required for assessing clapper rail habitat suitability cannot be made reliably using SVI data alone. Spectral vegetation indices obtained from *S. foliosa* are controlled by multiple aspects of its canopy structure, including leaf length, leaf numbers, horizontal/vertical leaf area, and proportion of non-photosynthetically active vegetation. Field data and research into the growth forms of *S. foliosa* indicate that SVIs are positively and significantly related to the plant's stem length only for short form plants (0 to 30 cm), which is consistent with short form *S. alterniflora* on the east coast of the United States (Hardisky *et al.*, 1983).

Regression model estimates of horizontally projected cover based on airborne multispectral digital camera data and a limited amount of plot-scale field measurements demonstrated that this approach was useful for making detailed estimates of cover over an entire restored wetland complex. Successful model implementation requires a preliminary classification of the wetland into low, middle, and high marsh types, which is also based on the airborne multispectral digital camera data. Maps of marsh type and cover estimates in each marsh type were produced in a relatively non-invasive manner with minimal field sampling. Marsh type and cover estimate maps complemented existing vegetation type maps of the restoration site and provided the basis for a georeferenced multi-temporal data set to examine rates of change and dynamics in cover.

Wetlands monitoring projects in San Diego County continue to use the baseline data set and approaches developed in this work on an annual basis. The data and analysis techniques employed may also be of use for other wetland monitoring projects in southern California and other coastal areas around the world. Further work is required to address the following: (1) more detailed assessment of the canopy condition and structure variables controlling *S. foliosa* spectral reflectance and SVI values (possibly through canopy radiation modeling); (2) calibration of ADAR data with hand-held radiometer data to apply relationships developed at single plot scale over images of wetlands to assess canopy condition and structure (NOT cover); (3) examination of red-edge shift and second-order scattering effects in the NIR spectral region associated with changes in canopy structure; and (4) spectral un-mixing of *S. foliosa* spectral reflectance values to examine the contribution of green vegetation non-photosynthetically active vegetation, substrate, and shade, and whether stem length may be inferred from the shade fraction.

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