

Seasonal Spectral Characteristics and Aboveground Biomass of the Tidal Marsh Plant, *Spartina alterniflora*

Spectral radiance indices were highly correlated with salt marsh biomass.

INTRODUCTION

SALT MARSHES form a more or less continuous band along the eastern coast of the United States (Reimold, 1977). The smooth cordgrass, *Spartina alterniflora* Loisel., is the dominant salt marsh plant, and the net primary production of this plant has been the focus of much research (Keefe, 1972; Turner, 1976). As an autotroph to both car-

necessary for continued marine productivity. Monitoring of salt marsh biomass and productivity, therefore, becomes very important.

A number of investigations explored the possibility of using the spectral characteristics of salt marsh vegetation, recorded on color infrared film, as a means of rapid salt marsh biomass inventories and eventual estimation of total salt marsh productivity (Stroud and Cooper, 1968; Gallagher and

ABSTRACT: *Seasonal changes in canopy spectral radiance for the salt marsh plant, Spartina alterniflora, were investigated. Short and tall growth forms were monitored using a hand-held radiometer spectrally configured to match bands 3, 4, and 5 of the Landsat-D (now Landsat-4) Thematic Mapper. Spectral radiance indices (vegetation index and infrared index) were highly correlated with canopy biomass parameters like live leaf biomass, percent live biomass, and a live-dead biomass ratio. Regression models equating spectral radiance index with the different canopy biomass parameters suggested that spectral data explained from 97 to 88 percent of the variation observed in the biomass data for short form communities. Tall form communities were generally less accurately described by spectral radiance data. Seasonal changes in S. alterniflora biomass were readily detected using spectral data. Quantitative remote sensing techniques such as described here can be used for estimating various biomass parameters in tidal wetlands.*

bon and nutrients, *S. alterniflora* is a major producer of fixed carbon for distribution to estuarine heterotrophs. Salt marshes are considered valuable ecosystems, intimately linked to the sea and

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Reimold, 1973; Reimold *et al.*, 1973). Ground based studies of the spectral properties of salt marsh plants (Carter and Anderson, 1972; Pfeiffer *et al.*, 1973) extended the effectiveness of subsequent spectral inventory techniques (Carter and Schubert, 1974; Klemas *et al.*, 1974; Klemas *et al.*, 1975; Carter, 1978; Bartlett and Klemas, 1980). With the advent of the Landsat satellites, more at-

tention was focused on fixed wavelength bands to describe vegetational characteristics.

Pearson *et al.* (1976), using a two-channel hand-held radiometer, found an excellent correlation between spectral data collected in the red (0.650-0.700 μm) and photographic infrared (0.775-0.825 μm) spectral regions and dry biomass of blue grama prairie grass. Using a similar radiometer, Drake (1976) described significant relationships between red or photographic infrared radiance and green standing crop biomass of two of the three salt marsh plant communities investigated. From these works, fixed bandwidths centered in the red region (where chlorophyll absorption was maximum) and in the near or photographic infrared region (where leaves are essentially transparent but can effectively scatter the radiation) appeared to hold promise for remote spectral estimation of gramineous biomass. In situ spectroradiometric data of upland grass canopies confirmed the usefulness of these spectral regions for biomass estimation (Tucker, 1977a; Tucker, 1977b).

The present research was designed to investigate the relationship between spectral radiance and various components of a *S. alterniflora* canopy over an entire growing season. In addition, a fertilizer treatment was included to demonstrate the performance of spectral radiance in describing a perturbation. Several height forms of *S. alterniflora* were also observed to document the occurrence of the infinite reflectance (Allen and Richardson, 1968) or the asymptotic nature of reflectance (Tucker, 1977c) as leaves become increasingly stacked in tall plant canopies.

METHODS

SITE DESCRIPTION

A homogeneous sward of short *Spartina alterniflora* was selected within the drainage basin of the Canary creek estuary in Lewes, Delaware. The study area was divided into plots measuring 1 m by 2 m with a 1-m pathway between rows and a 30-cm border between adjacent plots. Control and nitrogen fertilization plots were selected randomly within rows and were replicated six times. The average height of the plant canopy was 30 to 35 cm.

Ditchbank *S. alterniflora* was selected from transects defining areas along the two mosquito ditches on either side of the short *S. alterniflora* area. Three replicates were selected for harvest from each ditch. Average canopy height for the ditchbank population was approximately 80 to 100 cm.

Creekbank *S. alterniflora* was chosen along a large lateral ditch directly downstream of the two mosquito ditches. The limits of the sampling area were defined along the bank. Specific plot locations were determined prior to sampling, with care

being taken to avoid slumping or other changing areas. Canopy height averaged about 1 to 1.2 m for the creekbank population.

FERTILIZER APPLICATION

Six plots in the short form *S. alterniflora* received a fertilizer treatment on 26 May 1980. A commercially available ammonium sulfate fertilizer was dissolved and injected into the marsh. The fertilizer solution was administered using a syringe fitted with an aluminum tube. The tube was inserted 10 to 12 cm below soil level and approximately 40 ml of solution were injected. Injections were on 15-cm centers over the entire plot. The overall rate of nitrogen enrichment was 14g N m⁻².

BIOMASS HARVESTING

Biomass harvests were conducted at five-week intervals beginning 1 June 1980 and continued throughout the growing season until November. The short *S. alterniflora* areas were harvested every five weeks and the ditch and creekbank areas were harvested every ten weeks beginning in July. Control and nitrogen plots in the short *S. alterniflora* area were harvested using a circular 0.1-m² quadrat. The ditch and creekbank plots were harvested within a 0.25-m² frame. Specific quadrat placement for harvesting was systematically predetermined such that an intact portion of each plot was maintained for radiometric measurements throughout the growing season.

All culms within the quadrat were clipped at soil level, bagged, and stored cold until sorting. Three of the six replicates of each *S. alterniflora* type were sorted into live leaves, live stems, dead leaves and stems, and inflorescences. Each component was washed with tap water, dried at 60°C to a constant weight, and massed to determine dry weight biomass. The remaining three replicates were sorted into live, dead, and inflorescence tissues. These samples were processed as were the others, but the live leaf and live stem biomass were estimated from the total live based on the ratio of the two components from the first three samples. All biomass values were expressed on a grams dry weight per metre square (gdw m⁻²) basis.

SPECTRAL DATA COLLECTION

Spectral data were collected radiometrically using a portable, hand-held, fixed-band radiometer. The instrument was a prototype to the GSFC Mark II three band radiometer (Tucker *et al.*, 1981). The radiometer contained three channels spectrally configured with interference filters to simulate bands 3, 4, and 5 of the Landsat-D (now Landsat-4) Thematic Mapper. The three spectral bands consisted of a red (0.63-0.69 μm , RED), a near infrared (0.76-0.90 μm , NIR), and a middle

infrared (1.55-1.75 μm , IR) band. These bandwidths were selected specifically to study vegetational characteristics and are considered superior to the multispectral scanner bandwidths presently used in Landsat (Tucker, 1978a). A complete description of the radiometer and transmission characteristics of the interference filters can be found in Tucker *et al.* (1980).

To ensure adequate representation of the plant canopy in question, six radiance measurements were collected from each plot in the short form *S. alterniflora* area and three measurements for each ditch and creekbank area. Radiance data were collected over or directly adjacent to the specific portion of marsh to be harvested and were collected no more than five days before the actual harvest. The hand-held detector module was leveled (by way of a bubble level affixed to the top) and held 88 cm above the short form canopy and 140 cm above the ditch and creekbank canopies. The instrument operator always held the detector module at arms length over the plot and always stood facing the sun. Radiance measurements were obtained during maximum diurnal sun intensity (1100 to 1500 hrs). Weather conditions varied from clear to hazy, cloud free to partly cloudy, or calm to breezy. A BaSO_4 panel was employed as a reflectance standard. The panel was leveled on the marsh surface and five replicate readings taken from 30 cm normal to the panel surface. The reference panel readings were taken just prior to or immediately following measurements of spectral radiance in the plots.

Individual spectral radiance measurements for each plot were averaged by band and the mean radiance was used in subsequent calculations. Single band radiance data were collected as $\text{watts m}^{-2} \text{sr}^{-1}$. The radiance values of the red, near infrared, and middle infrared bands were combined as simple two-band ratios or as a normalized difference (Kreigler *et al.*, 1969). Expressing spectral radiance as ratios reduced temporal variations in irradiance attributable to seasonal changes in solar zenith angle and various atmospheric conditions encountered over the study period. Percent reflectance was calculated from the radiance measurements as the ratio of plant canopy radiance to the standard reference panel radiance for any given band.

Statistical analyses and regression analyses were conducted using the established algorithms of Nie *et al.* (1975). Data were transformed to natural logarithms, then substituted into linear least-squares regression procedures.

RESULTS

SHORT FORM—CONTROL AND FERTILIZED AREAS

Seasonal variation of live and dead components of the short *S. alterniflora* canopy in the control plots was compared with spectral radiance (Figure

1). Spectral radiance was represented as the vegetation index (VI) after Rouse *et al.* (1973) and was equivalent to $\text{NIR-RED}/\text{NIR+RED}$, where RED equals the red band radiance and NIR equals the near infrared radiance. Live biomass increased from June until August, after which total biomass peaked in September. The dead biomass exhibited a continual accumulation from June through November. The spectral radiance index peaked in August and declined thereafter. The pattern of seasonal radiance index fluctuation coincided with changes in the live component and not necessarily with total aboveground biomass or dead biomass.

Figure 2 presents data for short form *S. alterniflora* fertilized with ammonium sulfate early in the season. The pattern of seasonal biomass fluctuation was similar to the control areas. However, the magnitude was always greater for the nitrogen fertilized plots. Both the live biomass and the spectral radiance index peaked in August and declined into November.

An analysis of variance comparing the vegetation indices of the control versus nitrogen plots revealed that the vegetation indices in the nitrogen plots were significantly greater ($\alpha = 0.05$) from June through September than the vegetation indices in the control plots. The vegetation indices were not significantly different between the control and nitrogen plots at the October and November harvests. Live biomass was significantly greater in the nitrogen plots than in the control plots from June through October. At the

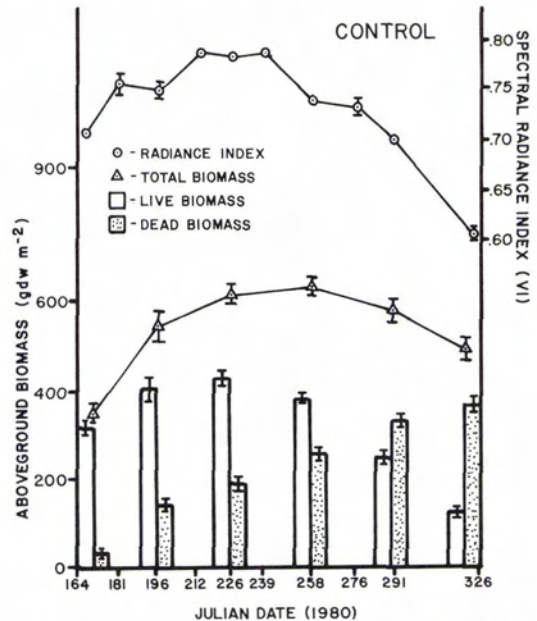


FIG. 1. Seasonal biomass and spectral radiance index for short form control marsh. Bars represent ± 1 std. error of the mean. VI = vegetation index.

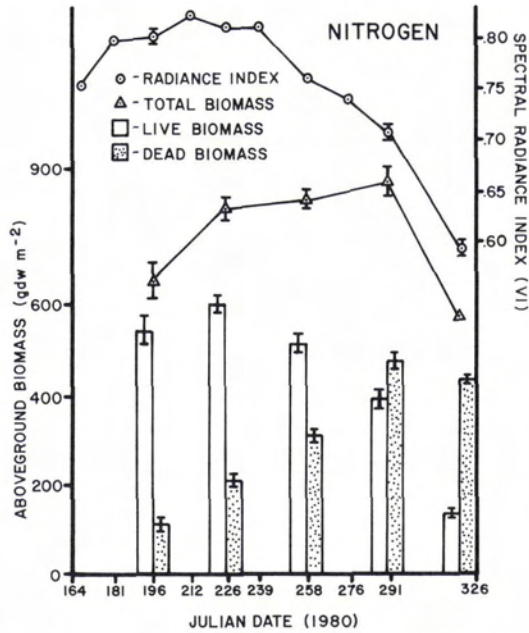


FIG. 2. Seasonal biomass and spectral radiance index for short form nitrogen fertilized marsh. Bars represent ± 1 std. error of the mean. VI = vegetation index.

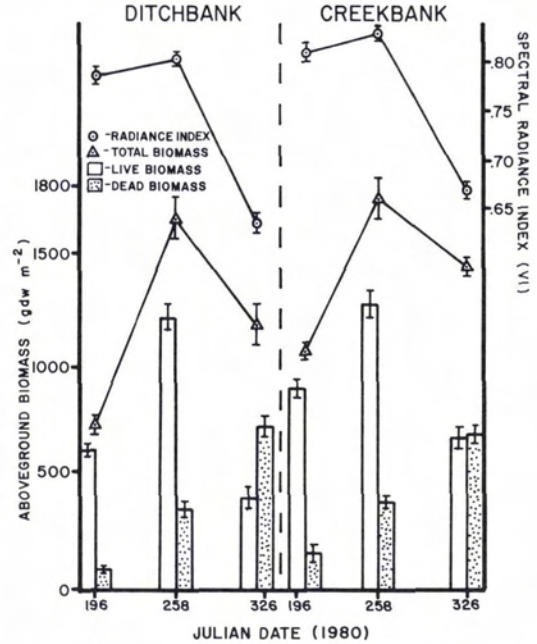


FIG. 3. Seasonal biomass and spectral radiance index for ditchbank and creekbank marsh. Bars represent ± 1 std. error of the mean. VI = vegetation index.

October harvest, live biomass was significantly different between treatments but the vegetation indices could not be statistically separated (at $\alpha = 0.05$). This was the only sampling interval in which the spectral radiance indices failed to describe statistically different amounts of live biomass.

TALL FORM—DITCHBANK AND CREEKBANK

Biomass and radiance data for the ditchbank and creekbank *S. alterniflora* populations are pictured in Figure 3. The vegetation index fluctuations closely followed the amount of live biomass present. The July harvest for both the ditchbank and creekbank areas showed lower total biomass and the November harvest. The radiance index values were much higher in July than in November. This disparity can be resolved by considering the live biomass, which was greater in July than in November. Ditchbank and creekbank populations attained their maximum biomass and vegetation index at the September harvest.

For each of the three harvest periods, the ditchbank and creekbank populations were statistically separable ($\alpha = 0.05$) using the spectral radiance index. The live biomass was also significantly different except at the September harvest. Total biomass, live biomass and dead biomass were not significantly different for the ditchbank and creekbank populations during the September harvest.

REGRESSION ANALYSIS

A number of canopy, biomass related, parameters were regressed against the spectral radiance indices. The control and nitrogen plots were treated separately and then combined. The same was done with the ditchbank and creekbank areas. The most significant relationships equated spectral radiance index with some form of the live biomass parameter (Table 1). Natural logarithmic transformations of the vegetation parameters improved the relationship and expanded the useful range of the equation. The spectral radiance data were expressed as either percent reflectance or simply upwelling radiance and were combined as band-to-band ratios or as the normalized difference. Regression results employing the different representations of spectral data were very similar; therefore, only the vegetation index (VI) and the infrared index (II) will be presented. The infrared index was similar to the vegetation index except that the middle infrared band was substituted for the red band in the computation of the index value.

Coefficients of determination from the regression analyses are listed in Table 1. The percent live biomass differed from the live-dead ratio in that the percent live biomass included live leaves and stems as the numerator and total aboveground biomass as the denominator. The live-dead ratio was simply the ratio of live leaf biomass to dead biomass. One would expect the live-dead ratio to

TABLE I. COEFFICIENTS OF DETERMINATION (r^2) RELATING THE RADIANCE INDEX AND PLANT CANOPY PARAMETERS FOR SHORT AND TALL FORM *S. alterniflora*

Spectral† Radiance Index	Vegetation* Parameter	SHORT FORM			TALL FORM		
		Control	Nitrogen	Combined	Ditchbank	Creekbank	Combined
VI	Live leaves	0.89	0.87	0.87	0.83	0.85	0.83
II	Live leaves	0.91	0.90	0.88	0.81	0.85	0.79
VI	% Live biomass	0.92	0.98	0.94	0.82	0.75	0.77
II	% Live biomass	0.96	0.97	0.97	0.68	0.74	0.67
VI	Live-dead ratio	0.92	0.97	0.94	0.83	0.75	0.79
II	Live-dead ratio	0.97	0.97	0.96	0.69	0.77	0.72

† VI = $(NIR - RED)/(NIR + RED)$; II = $(NIR - IR)/(NIR + IR)$.

* Natural log of each vegetation parameter was equated with spectral radiance; Live leaves = live leaf biomass $gdw\ m^{-2}$; % live biomass = live biomass/total aboveground biomass; Live-dead ratio = live leaf biomass/dead biomass.

be more representative of what the radiometer actually is sensing as opposed to the percent live biomass. The biomass of control and nitrogen plots for short *S. alterniflora* was estimated with similar accuracy by the spectral radiance indices. The biomass data were then combined, with the infrared index explaining as much as 88 percent of the variation of live leaf biomass, 97 percent of the variation in percent live biomass, and 96 percent of the variation in the live-dead ratio. The infrared index showed a slight improvement in describing the plant biomass over the vegetation index for the short form areas.

S. alterniflora generally showed a greater disparity between ditchbank and creekbank populations than was evident between control and nitrogen plots. This was attributed to the greater variability among plots of tall form and the height difference between ditchbank and creekbank might indicate a slightly different canopy geometry. The combined regression models for tall form yielded a maximum of 83 percent, 77 percent, and 79 percent of the variation in live leaf biomass, percent live biomass, and live-dead ratio, respectively, being explained by the vegetation index. The vegetation index tended to exhibit a higher correlation with the biomass parameters than the infrared index for the tall form communities.

The regression models for short and tall *S. alterniflora* (the combination of control and nitrogen plots and combination of ditch and creekbank plots) are presented in Tables 2 and 3. The models were developed with data collected from July through November. The standard error of the estimate for the radiance and vegetation parameter is also presented. The number of observations used for the short form models was 60 and for the tall form models was 36.

DISCUSSION

Spectral radiance data were particularly effective in detecting variations in live biomass early in

the growing season, but were less effective in October and November. This observation was most evident when monitoring the short *S. alterniflora* canopies. We would attribute the apparent loss of spectral sensitivity to the reduction of live biomass relative to dead biomass and to a greater solar zenith angle late in the growing season in conjunction with the rather compact (vertically) canopy of the short *S. alterniflora*. As the solar zenith angle increases, the irradiance per unit surface area decreases as a function of the cosine of the zenith angle. Kriebel (1976, 1978) has suggested that reflected radiance can change ± 1 percent per degree of change in solar zenith angle for vegetated targets. Also, the near vertical configuration of leaves and stems within the short form canopy would accentuate shadows within the canopy, thus reducing the effective area of illuminated vegetation when viewed at a 0° look angle. These factors were probably most important in attenuating the irradiance, yielding the apparent loss of spectral sensitivity in the reflected signal. The spatially less compact and greater proportions of live biomass in ditchbank and creekbank canopies probably suffered less from these seasonal problems, as indicated by their significant spectral separability in November. Some of the observed radiance attenuation was probably site and day specific, since spectral discrimination of canopy characteristics in short *S. alterniflora* has been demonstrated as late as November (Hardisky, 1981).

The dead component of the *S. alterniflora* canopies had little apparent correlation with changes in spectral radiance index. Gausman *et al.* (1976) found that the infinite reflectance of dead leaves was attained for a stack of three leaves, whereas live leaves could be layered eight times before reflectance became saturated. This would suggest that only dead vegetation near the top of the canopy would effectively influence reflectance; thus, biomass occurring deep in the canopy would remain undetected. Tucker (1978b), using

TABLE 2. REGRESSION MODELS EQUATING THE SPECTRAL RADIANCE INDEX WITH SELECTED CANOPY VARIABLES FOR SHORT *S. alterniflora*

MODEL*	Std. Error† of Est. Radiance	Std. Error° of Est. Vegetation	r ²
VI = 0.393 + 0.068 ln (L)	0.026	4.74	0.87
VI = 0.071 + 0.166 ln (P)	0.018	0.02	0.94
VI = 0.762 + 0.054 ln (D)	0.017	0.01	0.94
II = 0.169 + 0.107 ln (L)	0.040	4.62	0.88
II = (-.346) + 0.262 ln (P)	0.021	0.02	0.97
II = 0.746 + 0.085 ln (D)	0.023	0.01	0.96

* VI = vegetation index; II = infrared index; L = live leaf biomass gdw m⁻²; P = % live biomass; D = ratio of live leaf to dead biomass.

† Standard error of the estimate of radiance index.

° Standard error of the estimate of the vegetation parameter (L, P, or D).

field spectroradiometric techniques, showed a significant relationship between spectral reflectance in the near infrared region (0.80 μm) and dry biomass of a recently senescent grass canopy. His regression was fairly linear over the biomass range he monitored (up to about 600 g m⁻²). This indicated that canopy geometry may also be important in determining dead biomass reflectance because, based on Gausman *et al.* (1976) laboratory results, one might suspect very little ability to discriminate quantities of dead biomass. It appears from our data that the live biomass component was most effective in regulating the spectral composition of the reflected radiation.

The red and near infrared bands comprising the vegetation index are the most frequently used spectral band combination for describing vegetation canopies. Our results confirmed the usefulness of these bands; however, the infrared index, substituting the middle infrared band for the red band, may also possess some utility for canopy characterization. For short *S. alterniflora*, a slight increase in linearity of the radiance index versus vegetation parameter models was evident when spectral radiance was expressed as the infrared index. This improvement was most pronounced in the control areas where live biomass and canopy cover were less than in the nitrogen plots. In a

shallow canopy like the short *S. alterniflora*, soil background can constitute a significant portion of the reflected radiation (Colwell, 1974). Several times during the course of the study, the marsh surface was covered with a thin layer of tidal water. The middle infrared band radiance would decrease to a greater extent than the red band radiance as a result of absorption by the wet soil surface. This absorption by surface water would reduce the soil background reflectance, leaving only the radiance from the vegetation. This attenuation of soil background in the canopy spectral radiance would understandably have a greater impact as the percent cover of the canopy decreased. The control plots, based on biomass density, had a more open canopy than did the nitrogen plots. The infrared index was not superior to the vegetation index in the tall form *S. alterniflora*. Considering the lower incident energy in the 1.55 to 1.75 μm spectral region as compared to the 0.63 to 0.69 μm spectral region (Gates, 1966) and the deep, more horizontally oriented tall form canopy, it seems reasonable to assume that soil background had much less if any impact in the radiance signal from the tall form plants.

When comparing the models in Tables 2 and 3, distinct variations related to canopy structure and biomass density between short and tall form

TABLE 3. REGRESSION MODELS EQUATING THE SPECTRAL RADIANCE INDEX WITH SELECTED CANOPY VARIABLES FOR TALL *S. alterniflora*

MODEL*	Std. Error† of Est. Radiance	Std. Error° of Est. Vegetation	r ²
VI = 0.045 + 0.123 ln (L)	0.033	25.87	0.83
VI = 0.028 + 0.177 ln (P)	0.039	0.05	0.77
VI = 0.754 + 0.061 ln (D)	0.037	0.09	0.79
II = 0.123 + 0.112 ln (L)	0.035	29.00	0.79
II = 0.134 + 0.155 ln (P)	0.043	0.06	0.67
II = 0.769 + 0.055 ln (D)	0.040	0.10	0.72

* VI = vegetation index; II = infrared index; L = live leaf biomass gdw m⁻²; P = % live biomass; D = ratio of live leaf to dead biomass.

† Standard error of the estimate of radiance index.

° Standard error of the estimate of the vegetation parameter (L, P, or D).

canopies are reflected in changes of slope between regression models. The models using the vegetation index as the radiance parameter and percent live biomass or the live-dead ratio as the vegetation parameter showed the greatest similarity between short and tall forms. This suggested that the relationship remained linear over a larger range of values. The vegetation index might be used to predict percent live biomass or live-dead ratio for both height forms using a single model. The asymptotic effect of high live biomass density associated with different height forms was demonstrated by Bartlett (1979) for *S. alterniflora* in Delaware marshes. The fractions of live and dead biomass can apparently be discriminated beyond the normal limit of spectral radiance index saturation for live biomass estimation.

Percent live biomass and live-dead ratio were very similar with respect to spectral radiance index. The live-dead ratio did not account for live stem or inflorescence biomass. The similarity of the two representations of live versus dead biomass suggested the live leaf biomass and the dead biomass were essentially controlling the radiance signal and that the stem and inflorescence biomass were highly intercorrelated with the live-dead ratio.

CONCLUSIONS

Highly significant relationships between *S. alterniflora* canopy biomass parameters and spectral radiance indices were found. Spectral radiance indices explained 88 percent, 97 percent, and 96 percent of the variation in live leaf biomass, percent live biomass, and live-dead biomass ratio, respectively, for a short form *S. alterniflora* marsh over the growing season. Similarly, 83 percent, 77 percent, and 79 percent of the variation in live leaf biomass, percent live biomass, and live dead biomass ratio, respectively, could be explained by radiance data for tall form *S. alterniflora*. Radiance expressed as the infrared index was most effective in biomass estimation for the short form marshes and the vegetation index was most effective in biomass estimation in the tall form marshes.

The disparity in spectral sensitivity between height forms was partially attributed to the influence of soil background on the reflected signal. The middle infrared band unique to the infrared index was attenuated by water absorption at the soil surface, leaving the majority of the reflected signal dependent upon the canopy. The red band, unique to the vegetation index, would not be attenuated as severely by surface water, thus depended upon significant absorption by chlorophyll to attain a radiance different from soil background radiance. The vegetation index was most effective in tall, more dense canopies where soil reflectivity would be essentially zero.

Spectral discrimination of canopy characteristics

was effective during the majority of the growing season. Some loss of spectral sensitivity was apparent late in the season (October-November). The amount of live biomass remaining in the canopy and physical limitations imposed by larger solar zenith angles likely controlled the late season biomass discrimination capabilities of spectral radiance.

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31 May - 3 June 1983

This 36th Annual Conference of the Society of Photographic Scientists and Engineers will include sessions on photoelectrophoresis, electronic imaging, graphic arts, microelectronics, ionic and electronic properties of silver halide materials and of non-silver materials, student papers, x-ray inspection at airports, diffusion transfer technology, and processing of color photographic materials. The following sessions are also proposed: Scientific and medical photography, laser recording, image stability, experimental design, non-silver photographic systems, new imaging technology, remote sensing, image display, business graphics, holography, and high speed image recording.

Persons interested in contributing papers should submit the title and a 25-50 word abstract not later than 1 February 1983 to either

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