David S. Bartlett
Marine and Applications Technology Division
NASA Langley Research Center
Hampton, VA 23665
Vytautas Klemas
College of Marine Studies
University of Delaware
Newark, DE 19711

In Situ Spectral Reflectance Studies of Tidal Wetland Grasses

Potential spectral discrimination of "low marsh" from "high marsh" plant communities in Delaware is greatest in early winter and poorest during late spring and early summer if Landsat-MSS spectral bands are used.

Abstract: *Field measurements of wetland spectral canopy reflectance in the Landsat-MSS wavebands were correlated with biotic factors. The highest single band correlations were observed between visible (MSS Band 4:0.5 μm to 0.6 μm and Band 5:0.6 μm to 0.7 μm) canopy reflectance and the percentage, by weight, of live (green) vegetation in the canopies of Spartina alterniflora (salt marsh cordgrass), Spartina patens (salt meadow grass), and Distichlis spicata (spike grass). Infrared canopy reflectance displayed significant but weaker dependence on canopy parameters such as live and total biomass and canopy height.*

The Band 7 (0.8 μm to 1.1 μm)/Band 5 (0.6 μm to 0.7 μm) reflectance ratio was found to be highly correlated with green biomass for S. alterniflora.

Highest spectral separability between the "low marsh" S. alterniflora and the "high marsh" Salt Hay (S. patens and D. spicata) communities in Delaware occurs during December.

Introduction

The literature indicates that the effects of soil reflectance, canopy structure, and leaf orientation are at least as important as individual leaf optical characteristics in determining composite canopy reflectance for marsh plants. Canopies composed of vertically oriented elements such as those of *Spartina alterniflora* (Salt marsh cordgrass) and *Juncus roemerianus* (needlerush) expose more soil, water, and shaded vegetation to aerial view, producing lower canopy reflectance than canopies composed of more horizontal elements (Carter and Anderson, 1972). In some species, canopy geometry is variable as, for example, *Spartina patens* (salt meadow grass) whose stems and leaves can be flattened or "lodged" by wind and water, producing elevated canopy reflectance relative to upright canopy forms (Bartlett *et al.*, 1977; Carter and Anderson, 1972).

Pfeiffer *et al.* (1973) showed radiometric data suggesting that the infrared reflectance of *S. alterniflora* varied in response to both the orientation and amount of vegetative material in the canopy. Reimold (1973) observed a similar relationship in color infrared photographs and concluded that biomass estimates for *S. alterniflora* might be based on variations in tone on aerial photographs. Drake (1976) used a field radiometer to follow the seasonal increase in biomass of three marsh vegetation communities: "shrub" (*Iva frutescens*), "grass" (*Spartina patens* and *Distichlis spicata*), and "sedge" (*Scirpus olneyi*). He noted high correlations ($r^2 = 0.74$ to 0.83) between visible reflectance (0.656 μm to 0.705 μm) and green biomass for both the "grass" and "sedge" communities. However, infrared reflectance was not well correlated with biomass in any of the communities.

Carter and Schubert (1974) made reflectance measurements of several wetlands communities during a period extending through the growing season (May to October) and produced time series

Photogrammetric Engineering and Remote Sensing,
Vol. 47, No. 12, December 1981, pp. 1695-1703.
0099-1112/81/4712-1695$02.25/0

plots of reflectance to aid in determining the optimal time for spectral discrimination of the communities using Landsat-MSS spectral data. Seasonal effects on spectral contrast between communities were produced by variability in canopy structure and composition. Carter and Anderson (1972) had previously noted that the increase in *S. patens* reflectance during the growing season (caused by "lodging" of leaves and stems) produced a crossover of visible reflectance signatures for this species relative to that of *S. alterniflora* during a four-month period from May to August. In May, *S. patens* reflectance at wavelengths less than 0.7 μm was lower than that of *S. alterniflora* but had increased to values higher than those of *S. alterniflora* in August.

The dependence of reflectance on canopy variables has been more extensively studied for terrestrial vegetation types. Pearson and Miller (1972), Tucker and Maxwell (1976), and Tucker (1977a), among others, have utilized field radiometric measurements to show that canopy reflectance in the visible and near-infrared can be quantitatively related to physical/biotic variables including percent soil cover, total biomass, green biomass, leaf water content, and chlorophyll content. Colwell (1974) used a digital model of radiation/canopy interactions to trace variability in reflectance to basic parameters such as leaf and soil reflectance and transmittance, leaf orientation, and leaf area indices. He concluded that both visible and infrared reflectance measurements can be used to estimate canopy biomass although infrared reflectance is the best "all-season" indicator because of its sensitivity to a greater range of biomass values and its tendency to reduce the effects of variable proportions of live and dead vegetation.

Field radiometry has great value in quantitative studies of vegetation canopy reflectance. Such studies allow examination of the potential information content of remotely sensed spectral data as well as clarifying the seasonal, systematic, and other constraints on remote-sensing applications. A systematic application of field radiometric and biometric techniques to selected, dominant wetland vegetation types has been carried out in the extensive mid-Atlantic coastal marshes of Delaware. The objective of the study was to gain a greater understanding of the patterns and sources of variability in reflectance of wetland canopies in Landsat-MSS spectral bands.

METHODS

Spectroradiometric measurements were made *in situ* using a prototype "Radiant Power Measuring Instrument" (RPMI) (Rogers *et al.*, 1973). The RPMI, designed for collection of spectroradiance data in wavebands identical to Landsat-MSS Bands 4 (0.5 μm to 0.6 μm), 5 (0.6 μm to 0.7 μm), 6 (0.7 μm to 0.8 μm), and 7 (0.8 μm to 1.1 μm), measures target, solar, and atmospheric radiative parameters necessary to solve Equation 1 for target spectral reflectance (ρ); that is,

$$\rho = \frac{(R - L_A)\pi}{\tau(\cos Z \cdot H_{sun} + H_{sky})} \qquad (1)$$

where

R = radiance measured by Landsat-MSS,
L_A = atmospheric path radiance scattered into the target beam,
τ = atmospheric beam transmittance,
Z = solar zenith angle,
H_{sun} = direct incident solar irradiance, and
H_{sky} = diffuse incident "sky" irradiance.

If measurements of upwelling radiance (R') are made near the surface (~2 m above canopy top in this case) by the RPMI, the atmospheric transmittance (τ) and path radiance (L_A) terms can be neglected, resulting in a simplified expression for characteristic reflectance measured *in situ* (ρ). i.e.,

$$\rho = \frac{\pi R'}{\cos Z \cdot H_{sun} + H_{sky}} \qquad (2)$$

where

R' = upwelling radiance measured near the surface by the RPMI.

The three spectroradiometric parameters (R', H_{sun}, and H_{sky}) were measured in the field for each of the four Landsat/RPMI wavebands using procedures described in previously published studies (Bartlett *et al.*, 1977; Rogers *et al.*, 1973). Landsat wavebands were chosen for study because of the availability of orbital data for comparison and the anticipated value of Landsat for repetitive evaluation of large areas of wetland at low cost.

Vegetation plots where radiometric measurements were made were also sampled for canopy height, live stem density, live (green) biomass, litter biomass, and total biomass. Three common species in the coastal marshes of Delaware were examined: *Spartina alterniflora*, *Spartina patens*, and *Distichlis spicata*. Sampling was carried out approximately every two weeks for a full year although the need for clear weather dictated some deviation from a regular sampling schedule. Biomass determinations were not made during the cold months (November to March) so that Tables 1 and 2 and Figures 1 through 4 contain data collected only during the growing season (April to October). No radiometric data were acquired in January (1977) because of adverse weather conditions and snow cover. Sampling was accomplished in five separate marsh areas along approximately 110 km of the Delaware Bay coastline in order to obtain representative variability in marsh habitat and tidal and salinity conditions.

Analysis of data included regression to identify significant relationships between canopy reflectance and biotic variables. Digital modeling of canopy interactions with radiation was employed to investigate the empirically derived relationships. On occasion, results of modeling will be cited as they elucidate empirical relationships although a detailed treatment of modeling efforts is beyond the scope of this paper. The model used was developed by G. H. Suits and is described in Suits (1972).

Results and Discussion

Dependence of Spectral Reflectance on Canopy Variables

Sampling performed in the field showed several significant relationships between near-surface canopy reflectance and biotic variables measured in the same plots. Tables 1 and 2 show results of regression analysis for *S. alterniflora* (Table 1) and a composite "Salt Hay" community composed of merged data sets for *S. patens* and *D. spicata* (Table 2). *S. patens* and *D. spicata* are quite similar in canopy morphology and display similar reflectance trends. As a result, they are difficult to differentiate in multispectral data. In addition, they occupy similar physical environments in the higher portions of the marsh. These two species are therefore often merged into a composite "high marsh" community which shall be designated here as Salt Hay.

Visible canopy reflectance of *S. alterniflora* (RPMI/MSS Bands 4:0.5 μm to 0.6 μm and 5:0.6 μm to 0.7 μm) is most strongly correlated with the percentage, by weight, of green vegetation in the canopy (Table 1). This is due to increased absorption of visible light in the canopy as the proportion of green, chlorophyll-bearing vegetation increases (Tucker, 1979). Correlation coefficients are higher for regression with Band 5 (0.6 μm to 0.7 μm) than Band 4 (0.5 μm to 0.6 μm) as a result of selective chlorophyll absorption of radiation in the "red" (Band 5) spectral region. The form of the relationship is somewhat species-specific and is both stronger and more nearly linear for *S. alterniflora* (Figure 1) than for Salt Hay (Figure 2) in spite of the very similar optical characteristics displayed by individual leaves of all the plants examined (Bartlett, 1979). Species-specific effects of canopy morphology rather than optical responses of individual leaves are therefore implicated in the differences observed. If month by month correlations are examined, the relationship between visible reflectance and percent green vegetation for *S. alterniflora* deteriorates late in the growing season during August, September, and October (Bartlett, 1979). It was observed that during this period green vegetation becomes more and more concentrated in the upper part of the canopy, resulting in high absorption regardless of the vertically integrated proportion of green vegetation, thus producing the poor correlations obtained. In the Salt Hay canopy, green material is concentrated at the top of the canopy throughout most of the growing season as new, green shoots extend above a recumbent mat of necrotic material early in the spring. This produces a rapid decay in visible reflectance to low values, even with relatively low percentages of green vegetation. The result is the intensely asymptotic relationship between

Table 1. Linear Coefficient of Determination (r^2) Matrix for *Spartina alterniflora*. $N = 65$ Except for Live Stem Density ($N = 50$)

		Green Biomass	Total Biomass	% Green Biomass	Canopy Height	Live Stem Density
In Situ Canopy Reflectance	Band 4	0.40*	0	0.55*	0	0
	Band 5	0.47*	0	0.72*	0.09	0
	Band 6	0.11	0.20	0	0.21	0.13
	Band 7	0.39	0.26	0.18	0.38	0.11
	Band 7 / Band 5	0.78	0	0.73	0.35	0
	Green Biomass	1	0.21	0.68	0.45*	0
	Total Biomass		1	0	0.21	0
	% Green Biomass			1	0.21	0
	Canopy Height				1	0.09
	Live Stem Density					1

* Non-linear regression of form $y = ax^b + c$. Parameters measured 9 April 1977 to 21 October 1977.

TABLE 2. LINEAR COEFFICIENT OF DETERMINATION MATRIX FOR "SALT HAY" (*S. PATENS* AND *D. SPICATA*). $N = 70$.

		Green Biomass	Total Biomass	% Green Biomass	Canopy Height	Live Stem Density
In Situ Canopy Reflectance	Band 4	0.43*	0	0.47*	0.08	0
	Band 5	0.57*	0	0.55*	0.10	0
	Band 6	0	0	0.07	0	0.08
	Band 7	0.15	0	0.25	0.05	0.08
	Band 7 / Band 5	0.33	0	0.45	0.19	0.13
	Green Biomass	1	0.15	0.75	0.06	0.35
	Total Biomass		1	0.05	0	0
	% Green Biomass			1	0.11	0.43
	Canopy Height				1	0.07
	Live Stem Density					1

* Non-linear regression of form $y = ax^b + c$. Parameters measured 9 April 1977 to 21 October 1977.

Band 5 reflectance and percentage of green vegetation found in Figure 2. If the effects of this vertical partitioning of the canopy are mitigated by examining only those Salt Hay plots in which both live and dead vegetation is in the lodged (recumbent) position, the correlation of Band 5 reflectance with the percentage of green vegetation is considerably strengthened ($r^2 = 0.76$, $n = 26$). Thus, as with *S. alterniflora,* it appears that vertical canopy heterogeneity degrades relationships for visible radiation.

Visible canopy reflectance was also found to be significantly correlated with the green biomass of the sample plots. Curvelinear relationships were observed having coefficients of determination of $r^2 = 0.47$ (Table 1) and $r^2 = 0.57$ (Table 2) for regression of 0.6 μm to 0.7 μm canopy reflectance with green biomass of *S. alterniflora* and Salt Hay, respectively. However, the results of digital simulation of canopy reflectance indicate that "red" reflectance is sensitive to green biomass only indirectly, through the high intercorrelation between green biomass and the percentage of green vegetation in the canopy (Tables 1 and 2: $r^2 = 0.68$ and 0.75 for *S. alterniflora* and Salt Hay, respectively). Application of the Suits (1972) model to a hypothetical canopy by Colwell (1974) and to simulation of *S. alterniflora* by Bartlett and

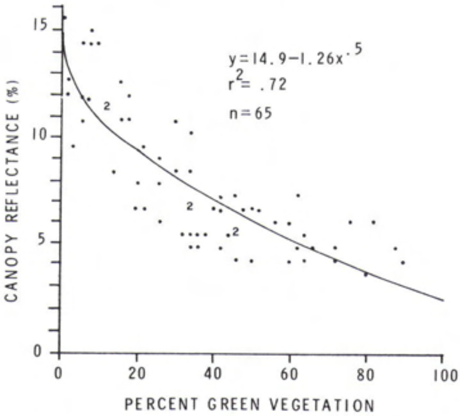

FIG. 1. Plot of Band 5 (0.6 μm to 0.7 μm) canopy reflectance versus percent green vegetation for *S. alterniflora*. Regression results are shown.

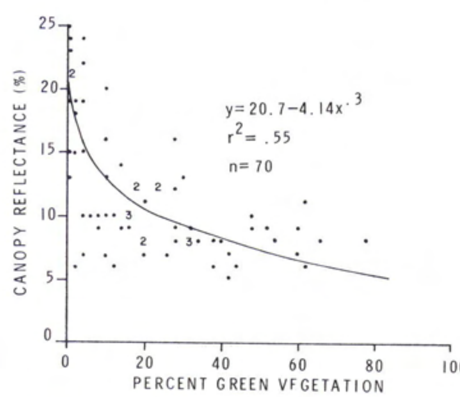

FIG. 2. Plot of Band 5 (0.6 μm to 0.7 μm) canopy reflectance versus percent green vegetation for Salt Hay. Regression results are shown.

Klemas (1980) has shown that the relative proportions of chlorophyll-bearing "green" vegetation and senescent or necrotic "brown" vegetation is functionally important in determining visible canopy reflectance, particularly in the "red" chlorophyll absorption spectral region. The actual amount (i.e., biomass) of vegetation present is parameterized in the model by the horizontally and vertically projected Leaf Area Index (horizontal LAI and vertical LAI). Increasing leaf area index does not significantly influence visible canopy reflectance over dark soils except at values of horizontal LAI less than about 1.0 (Colwell, 1974). Such low values of horizontal LAI represent a relatively sparse canopy which may be found during early stages of crop development but which is not often observed in tidal wetlands. Horizontal leaf area indices measured for *S. alterniflora* were never below 1.0 (Bartlett, 1979). It is also noted that visible reflectance is completely uncorrelated with total biomass (Tables 1 and 2), further indicating that coverage of soil by varying amounts of vegetation does not significantly affect visible canopy reflectance.

Infrared canopy reflectance is not related to biotic variables as clearly as is visible reflectance. (Similar characteristics were observed in both RPMI Band 6 (0.7 μm to 0.8 μm) and Band 7 (0.8 μm to 1.1 μm). Band 7 will be used to illustrate infrared relationships.) Infrared canopy reflectance in the 0.8 μm to 1.1 μm spectral region is correlated most strongly with green biomass ($r^2 = 0.39$) and canopy height ($r^2 = 0.38$) for *S. alterniflora* (Table 1) and with the proportion of green vegetation ($r^2 = 0.25$) for Salt Hay (Table 2). Figure 3 shows RPMI/Band 7 canopy reflectance plotted against green biomass of the measured *S. alterniflora* plots. Although the correlation is not strong, it is highly significant as are coefficients of variation (r^2) for total biomass and canopy height,

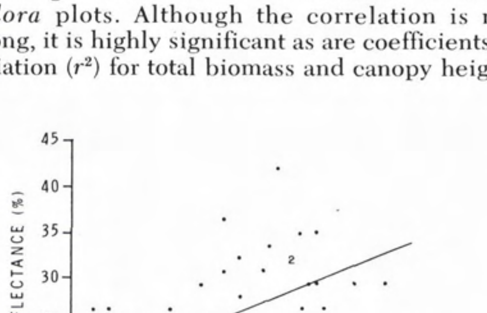

FIG. 3. Plot of Band 7 (0.8 μm to 1.1 μm) canopy reflectance versus green biomass for *S. alterniflora*. Regression results are shown.

accounting for greater than a third of the variation in canopy reflectance (Table 1). Such a result is in general agreement with other investigations such as those of Pearson and Miller (1972), Colwell (1974), Tucker and Maxwell (1976), and Tucker (1978). Model studies conducted by Colwell (1974) and Bartlett and Klemas (1980) indicate functional dependence of infrared reflectance on leaf area index. Total LAI is most important, although increased transmittance of green leaves can produce enhanced response to green leaf area index (Colwell, 1974). Biomass information is thus available to the extent that it is correlated with leaf area index or percent soil coverage (Colwell, 1974). This relationship will be species-specific as it depends upon the morphology of the canopy. Note that the density of live stems is very poorly correlated with biomass and infrared canopy reflectance for these wetland grasses (Tables 1 and 2). This appears to be caused by a weak relationship between stem density and total LAI; high density stands tend to be composed of small individual plants and vice versa.

The degraded sensitivity of infrared reflectance to biomass-related parameters for Salt Hay (Table 2: $r^2 = 0.15$ and 0.05 for green biomass and canopy height, respectively) may result from variability in canopy structure (upright versus lodged stands) the extreme density of the lodged canopy and the high proportion of stem material which limit penetration of infrared radiation into the canopy. If lodged plots are eliminated from the Salt Hay data set, correlations of infrared reflectance with green biomass are increased to values comparable to that for *S. alterniflora* while consideration of lodged stands alone produces no such enhancement of the relationship. This would seem to indicate that the characteristic high density of the Salt Hay canopy, enhanced by lodging, degrades infrared response to biomass. To a lesser degree, the lush canopy of *S. alterniflora* during most of the year may be responsible for the relatively weak correlations of infrared reflectance with canopy parameters for this species.

The dependence of canopy reflectance on biotic variables in these wetland grasses fits generally into the pattern observed in terrestrial studies. However, wetland canopies have some distinctive characteristics which enhance or obscure the effects of particular variables with significant implications for remote sensing:

(1) Natural tidal wetland grasses are characterized throughout the year by a relatively thick canopy composed of variable amounts of living and dead vegetation which is not appreciably grazed or harvested as are rangeland or agricultural canopies. Because leaf area indices are generally high, soil coverage is also extensive, resulting in a substantial lack of functional dependence of visible reflectance on biomass. Lack of reflec-

tance contrast between vegetation and dark marsh soils also reduces the effects of biomass on visible canopy reflectance. Instead, contrast within the canopy between live (green) and dead (brown) vegetation dominates visible canopy reflectance. As visible radiation "sees" only the upper portions of the canopy, vertical canopy heterogeneity can degrade the reflectance associations. However, during most of the growing season, the *S. alterniflora* canopy is quite homogeneous resulting in a strong relationship (Figure 1).

(2) The large amounts of vegetation present may also restrict the sensitivity of infrared reflectance to biomass-related variables. Characteristically high leaf area indices, along with canopy morphology (in the case of "lodged" Salt Hay), limit the penetration of infrared radiation into the canopy despite the high transmissivity of individual leaves. Whatever the cause, there appears to be considerably less sensitivity of infrared reflectance to biomass-related variables for these wetland grasses than has been reported for other vegetation types.

Nevertheless, there is considerable potential for spectro-radiometric monitoring of significant canopy variables, particularly green biomass, for *S. alterniflora*. Figure 4 shows results of regression of the infrared/red reflectance ratio with green biomass for *S. alterniflora*. The success of this ratio in tracking variability in vegetative biomass is well documented for terrestrial vegetative types (Pearson and Miller, 1972; Colwell, 1974; Tucker and Maxwell, 1976; Tucker, 1977a; Tucker, 1979) and is attributed by most to (1) the opposing trends in correlation (one negative, one positive) with increasing biomass of the two bands and (2) normalization of the effects of variability in

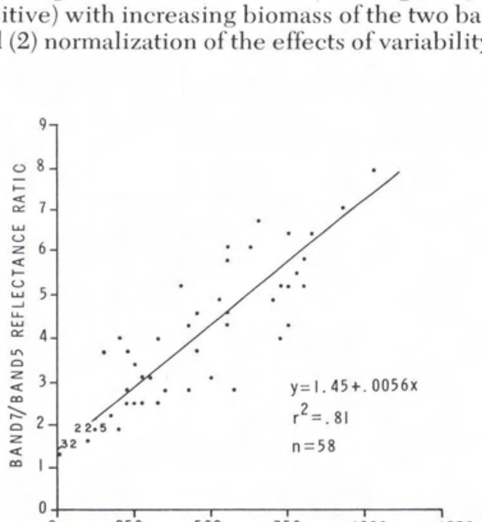

FIG. 4. Plot of Band 7/Band 5 canopy reflectance ratio versus green biomass for *S. alterniflora*. Regression results are shown. Data collected April through September.

soil reflectance. However, neither mechanism would appear to pertain to wetlands where high LAI values preclude significant sensitivity of visible reflectance to biomass and where soil reflectance is uniformly low due to high moisture and organic content. Rather, it seems more likely that the response of the IR/red reflectance ratio is based on the sensitivity of red reflectance to the proportion of green vegetation in the canopy. When normalized by infrared reflectance which responds directly to increases in the amount of biomass (or leaf area index) present, the result is a parameter sensitive to green biomass. Particular sensitivity to green biomass of terrestrial plants was noted by Pearson and Miller (1972) and Tucker (1979).

In most studies where spectral analysis has been applied to the full range of biomass present, the reflectance relationship behaved asymptotically, displaying reduced sensitivity to increasing biomass as large biomass values were encountered (Colwell, 1974; Tucker, 1977b and 1978). A linear regression model is quite adequate, however, for the entire range of biomass observed in *S. alterniflora* (Figure 4). This result is related to the near-linearity of the red reflectance relationship with the proportion of green vegetation (Figure 1) for this species. Tucker (1979) noted that the presence of significant amounts of standing dead vegetation tends to linearize the IR/red versus green biomass relationship. Figure 1 shows that the majority of wetland plots contained 40 percent or more dead vegetation. The data shown in Figure 4 were collected from April through September when most plant growth takes place in Delaware. During that time, the form and strength of the relationship vary only slightly so that the same model may be used throughout the growing season. The correlation deteriorates in the fall due to the appearance of vertical canopy heterogeneity but, as little new growth takes place between October and March, loss of biomass information during this period is of minor consequence in production estimates.

The Band 7/Band 5 reflectance ratio is also linearly correlated with the proportion of green vegetation in the canopy (Table 1: r^2 = 0.73). A similar trend is reported by Colwell (1974) and suggests the possibility of monitoring total as well as live biomass throughout the growing season.

SEASONAL VARIABILITY IN CANOPY REFLECTANCE

The composition and structure of wetlands canopies on which spectroreflectance has been shown to depend is seasonally variable, particularly in temperate climates such as encountered in Delaware. As a consequence, the variability in reflectance of wetland canopies is time dependent and may be expected to affect the spectral discriminability of species and communities. A frequently performed task in tidal marsh inventories is the discrimination of "low marsh" (dominated by *S. alterniflora*) from "high marsh" (dominated in Delaware by Salt Hay—*S. patens* and *D. spicata*). This distinction is important for inferences to be made concerning hydrologic regimes and habitats present. Figures 5 and 6 show the RPMI-measured monthly means and standard deviations of *S. alterniflora* and Salt Hay canopy reflectance in Bands 5 (0.6 μm to 0.7 μm) and 7 (0.8 μm to 1.1 μm), respectively. Considerable divergence in the trends is obvious as are qualitative similarities in seasonal patterns of change. Visible canopy reflectance, particularly in Band 5 (0.6 μm to 0.7 μm), is at a maximum during winter and decreases to a minimum during summer when absorption by green vegetation is greatest (Figure 5). Winter visible reflectance of Salt Hay is significantly higher than that of *S. alterniflora* due to the high reflectivity of the dense mat of necrotic Salt Hay in contrast to the more sparse, vertically oriented stems and leaves of *S. alterniflora*. During spring, visible reflectance of Salt Hay drops quite rapidly as new, green growth quickly obscures and shades the mat of litter below. The new growth of *S. alterniflora*, on the other hand, does not appear at the top of the largely vertical canopy until later in the summer, resulting in a more gradual lowering of canopy reflectance. A period of signature overlap in the visible wavebands during May, June, and July is produced by the differential rates of decrease in reflectance (Figure 5). An identical "signature reversal" between *S. alterniflora* and *S. patens* was found by Carter and Anderson (1972) in Maryland marshes. In late fall and early winter, the maximum divergence in visible reflectance signatures is observed resulting from a faster and more complete die-off of the Salt Hay than the *S. alterniflora* (Figure 5).

Infrared canopy reflectance increases from a minimum in early spring to a maximum in July, then decreases during the late summer (Figure 6). The spring increase in reflectance is quite small in *S. alterniflora* despite the increases in canopy biomass and height taking place during the period.

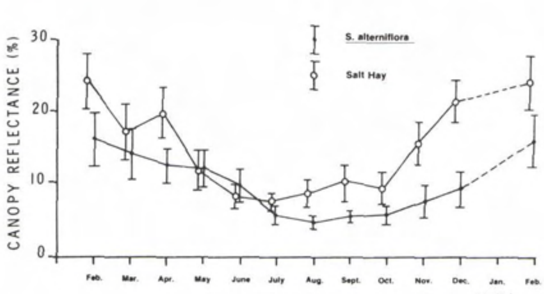

FIG. 5. Monthly means and standard deviations of Band 5 (0.6 μm to 0.7 μm) canopy reflectance for *S. alterniflora* and Salt Hay.

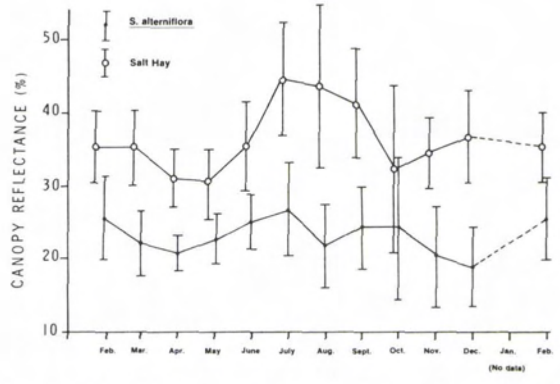

FIG. 6. Monthly means and standard deviations of Band 7 (0.8 μm to 1.1 μm) canopy reflectance for *S. alterniflora* and Salt Hay.

In Salt Hay, the summer increase is considerably enhanced by the tendency of new shoots to lodge into more highly reflective mats as their length increases. Again, similar trends have been observed by Carter and Anderson (1972) working with *S. alterniflora* and *S. patens*.

The significance of these species-specific seasonal trends in canopy reflectance for remote sensing is clear. When spectral criteria are used to discriminate "low marsh" *S. alterniflora* from "high marsh" Salt Hay, as in automated analysis of Landsat-MSS data, imagery acquired at times when divergence in spectral reflectance is greatest should be preferred. This divergence or "spectral separability" can be represented by the difference in the mean reflectance of the two vegetation types normalized by the summed standard deviation in reflectance for both types, and is plotted monthly through the year in Figure 7. Some separability is present during most months, but signature convergence during May, June, and July

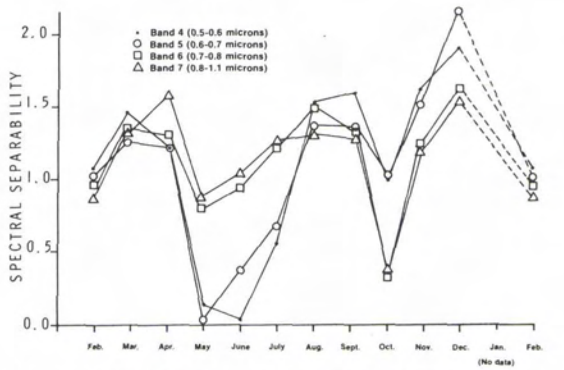

FIG. 7. Monthly spectral separability between *S. alterniflora* and Salt Hay expressed as difference in mean canopy reflectance divided by summed standard deviations.

virtually eliminates separability in the visible Bands 4 and 5 and is present to some degree in the infrared as well. The optimal time for spectral discrimination of these two vegetation types would appear to be December when visible and infrared reflectance separability is uniformly high (Figure 7). The one-month drop in separability during October is produced largely by increases in standard deviation of the respective signatures (Figure 6) and its lack of persistence suggests an anomalous data set during this month.

Conclusions

The application of *in situ* radiometry and standard field biometric techniques to tidal wetland grasses has produced the following major conclusions with regard to the observed variability in canopy reflectance:

(1) Much of the variability in reflectance is produced by changes in canopy morphology and composition: both interspecific, as between the S. *alterniflora* canopy versus more dense Salt Hay; and intraspecific, as in the distinct growth forms of Salt Hay.

(2) The extensive soil coverage, which is characteristic of wetland canopies throughout the year, results in primary dependence of visible canopy reflectance (Landsat-MSS Bands 4 and 5) upon the relative proportions of live (green) and dead (brown) vegetation within the canopy. The actual amount of vegetation (biomass) present is related to visible reflectance only insofar as it is correlated with the proportion of live or dead material.

(3) Infrared canopy reflectance (Landsat-MSS Bands 6 and 7) is somewhat sensitive to the amount of vegetation present but infrared response is also controlled by growth form. The response appears to be restricted by the comparatively lush growth found in wetland grasses which limits penetration, even of infrared radiation, into the canopy.

(4) The Band 7/Band 5 reflectance ratio is quite sensitive to changes in green biomass of S. *alterniflora* over a range of biomass from 0 to ~1000 g dry wt/m^2. This ratio is also correlated with the proportion of green vegetation within the canopy. There appears to be considerable potential for radiometric monitoring of live and dead biomass of S. *alterniflora* throughout the temperate growing season and subsequent estimation of net primary productivity using Landsat-MSS spectral bands.

(5) Seasonal divergence and convergence of reflectance signatures is a significant process affecting spectral discriminability of important wetland vegetation types. Potential spectral discrimination of "low marsh" (S. *alterniflora*) from "high marsh" (S. *patens* and D. *spicata*) plant communities in Delaware is greatest in early winter and poorest during late spring and early summer if Landsat-MSS spectral bands are used.

Acknowledgments

This research was supported, in part, by NASA Grant No. NAS5-20983 and the University of Delaware, College of Marine Studies. The authors are grateful to Dr. G. H. Suits for the use of his canopy reflectance model, to Dr. R. C. Harriss for his critical review of the text, and to Ms. Karen Copley for preparation of the manuscript.

References

Bartlett, D. S., 1979. *Spectral reflectance of tidal wetland plant canopies and implications for remote sensing.* Ph.D. Dissertation, University of Delaware, Newark, Delaware: 238 p.

Bartlett, D. S., and V. Klemas, 1980. Quantitative assessment of tidal wetlands using remote sensing. *Environmental Management* 4(4): pp. 337-345.

Bartlett, D. S., V. Klemas, R. H. Rogers, and N. J. Shah, 1977. Variability of wetland reflectance and its effect on automatic categorization of satellite imagery. *Proc. Am. Soc. of Photogram. Ann. Mtg.*, Washington, DC: pp. 70-89.

Carter, V. P., and R. R. Anderson, 1972. Interpretation of wetlands imagery based on spectral reflectance characteristics of selected plant species. *Proc. Am. Soc. of Photogram. 38th Ann. Mtg.*, Washington, DC: pp. 580-595.

Carter, V. P., and J. Schubert, 1974. Coastal wetlands analysis from ERTS MSS digital data and field spectral measurements. *Proc. 9th Internatl. Symp. on Remote Sensing of Environment*, Ann Arbor, Michigan, Vol. II: pp. 1241-1259.

Colwell, J. E., 1974. Grass canopy bidirectional spectral reflectance. *Proc. 9th Internatl. Symp. on Remote Sensing of Environment*, Ann Arbor, Michigan, Vol. II: pp. 1061-1085.

Drake, B. G., 1976. Seasonal changes in reflectance and standing crop biomass in three salt marsh communities. *Plant Physiol.* 58: pp. 696-699.

Pearson, R. L., and L. D. Miller 1972. *Remote spectral measurements as a method for determining plant cover.* U.S. Internatl. Biological Program, Colorado State University, Tech. Rept. #167: 48 p.

Pfeiffer, W. J., R. A. Linthurst, and J. L. Gallagher, 1973. Photographic imagery and spectral properties of salt marsh vegetation as indicators of canopy characteristics. *Am. Soc. of Photogram., Symp. on Remote Sensing in Oceanography*, Lake Buena Vista, Florida, Part II: pp. 1004-1016.

Reimold, R. J., J. L. Gallagher, and D. E. Thompson, 1973. Remote sensing of tidal marsh, *Photogram. Eng.* 39 (5): pp. 477-488.

Rogers, R., K. Peacock, and N. Shah, 1973. A technique for correcting ERTS data for solar and atmospheric effects. *Third ERTS Symp.*, Goddard Space Flt. Center, Greenbelt, Maryland, NASA SP-351: pp. 1787-1804.

Suits, G. H., 1972. The calculation of the directional reflectance of a vegetative canopy. *Remote Sensing of Environment*, 2(1): pp. 117-125.

Tucker, C. J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8: pp. 127-150.

———, 1977a. Spectral estimation of grass canopy variables. *Remote Sensing of Environment*, 6(1): pp. 11-26.

———, 1977b. Asymptotic nature of grass canopy spectral reflectance. *App. Optics*, 16(5): pp. 1151-1156.

Tucker, C. J., and E. L. Maxwell, 1976. Sensor design for monitoring vegetation canopies. *Photogram. Eng. and Remote Sensing* 42(11): pp. 1399-1410.

(Received 21 October 1980; revised and accepted 23 May 1981)

CALL FOR PAPERS

Symposium on the Study of Land Transformation Processes from Space and Ground Observations

Ottawa, Canada
31 May - 2 June 1982

Sponsored by the Committee on Space Research (COSPAR), the Scientific Committee on Problems of the Environment (SCOPE), the International Astronautical Federation (IAF), and the United Nations Environmental Program (UNEP), this Symposium is organized in recognition that space observations, coupled with meaningful ground-collected information, are pivotal to a proper understanding of the role of human activity and natural processes in regional-scale land transformation and changes in eco-systems.

Contributed papers are solicited that describe the use of space and/or ground observations to study regional land transformation resulting from

- Human activities such as population redistribution, urbanization/industrialization, changes in agriculture/forestry/grassland management, shifts in the approaches to the natural resource utilization; or
- Natural phenomena such as changes in climate, wind, or fluvial processes.

Abstracts and requests for additional information should be sent by *15 January 1982* to

Dr. Robert M. Ragan
Remote Sensing Systems Laboratory
University of Maryland
College Park, MD 20742

CALL FOR PAPERS

35th Annual Conference Society of Photographic Scientists and Engineers

Rochester, New York
9-14 May 1982

The Conference will include the following sessions: Electrophotography, photovoltaics, and photoconductivity; fundamental photophysical process in photosensitive inorganic systems; spectral sensitization; chemical sensitization; optical disk and storage; image quality; processing of silver halide materials; and chemical and energy recovery.

Title and brief abstract (25 to 50 words) should be sent by *31 January 1982* to

Dr. Alfred Marchetti
Eastman Kodak Company
343 State Street
Rochester, NY 14650
Tele: (716) 724-5704