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Temporal Measurement And Analysis Of High-Resolution Spectral Signatures Of Plants And Relationships To Biophysical Characteristics

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ABSTRACT

Measurements of temporal reflectance signatures as a function of growing season for sand live oak (*Quercus geminata*), myrtle oak (*Q. myrtifolia*) and saw palmetto (*Serenoa repens*) were collected during a two year study period. Canopy level spectral reflectance signatures, as a function of 252 channels between 368 and 1115 nm, were collected using near nadir viewing geometry and a consistent sun illumination angle. Leaf level reflectance measurements were made in the laboratory using a halogen light source and an environmental optics chamber with a barium sulfate reflectance coating. Spectral measurements were related to several biophysical measurements utilizing optimal passive ambient correlation spectroscopy (OPACS) technique. Biophysical parameters included percent moisture, water potential (MPa), total chlorophyll, and total Kjeldahl nitrogen. Quantitative data processing techniques were used to determine optimal bands based on the utilization of a second order derivative or inflection estimator. An optical cleanup procedure was then employed that computes the double inflection ratio (DIR) spectra for all possible three band combinations normalized to the previously computed optimal bands. These results demonstrate a unique approach to the analysis of high spectral resolution reflectance signatures for estimation of several biophysical measures of plants at the leaf and canopy level from optimally selected bands or bandwidths.

2. INTRODUCTION

Determination of water status, foliar chemistry, and other biophysical features of vegetation has become commonly recognized as a primary objective for remote sensing in terrestrial ecology and earth system science.[1,2,3] Remote sensing can provide researchers access to spatial and temporal data necessary for development, parameterization and testing of local, regional, and global scale ecosystem and environmental process models allowing us to extend our understanding beyond what has been historically limited to a point based system for data collection and model validation. Subtle changes in ecosystem functioning may be expressed in plant canopy biochemistry as a result of altered metabolic processes, carbon allocation patterns, and nutrient availability. The potential to remotely estimate canopy constituents depends partly on the influence of the parameter on the reflectance signature.[4] Organic bonds found in foliar mass exhibit vibrational stretching modes that absorb radiation at frequencies in the middle infrared part of the spectrum. Chlorophyll and other carotenoid pigments display strong absorption in the visible part of the spectrum due to electron energy transitions.[5] Potential applications of remote sensing techniques that allow for spatial and temporal estimation of biophysical conditions include agricultural land management (e.g. irrigation, fertilization, pest management), exotic plant control, and wildlife habitat management including utility in both fire and water level manipulations.

The optical determination of leaf water content or water status has been the subject of much research during the last 30 years utilizing a variety of instruments and analytical approaches under many environmental conditions.[6,7,8,9,10] Early works utilized regression techniques to study the relations among reflectance of single leaves and measures of water content.

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Thomas et al.[11] focused on the 1.45 and 1.93 μm wavelength water absorption band regions. These researchers found that linear regression techniques, logarithmic functions and second-degree polynomial equations could be utilized to describe the relationship between reflectance at the specified wavelengths and measures of water content or leaf turgidity in the laboratory. In general, reflectance increased as total water content or leaf turgidity decreased. A noted limitation was that relative water content and turgidity varied over a wide range up to and including the point of leaf wilting before reflectance was appreciably affected. Also, it was suggested that changes in observed reflectance may have been a function of changes in the internal leaf structure from the reduction in turgidity and not necessarily reduced absorption from decreases in water content.

Studies of the potential for utilizing several indices such as the Moisture Stress Index (MSI) defined as the ratio of the middle-infrared (1.55-1.65 um) to near-infrared (0.76-0.90 um) reflectance and a more complex ratio type leaf, water content index (LWCI), to estimate changes in leaf water status, relative water content (RWC) or equivalent water thickness (EWT) have been conducted.[6,7,13] At the laboratory or leaf scale, these approaches appear promising with linear regressions between the MSI and LWCI indices and RWC generally producing correlation coefficients between 0.75 and 0.92 and 0.92 and 0.99, for MSI and LWCI respectively. The LWCI required collection of reflectance data at two known RWC levels rendering it impractical for most outdoor remote sensing activities. In addition, when the MSI was applied to aircraft and satellite data collected at the canopy level the method was not sensitive to small changes in leaf water content normally associated with water stress. Estimates of the amount of water loss required for detection of significant changes in the MSI were roughly 50% .

Penuelas, et al.[9] described the use of reflectance at the 950-970 nm region as an indicator of plant water status. These researchers utilized the ratio between a water absorption band at 970 nm with a reference band at 900 nm. Their results suggest that within the RWC range of 80-90%, reflectance changes were small and not significantly detectable. When the RWC fell below approximately 80% and water stress was well developed, statistically significant changes in the reflectance ratios were observed. These changes were believed to be a function of cell wall elasticity and the resulting changes in the internal structure of the leaf as water turgor pressure dropped. Other factors that may have influenced the use of their approach included canopy gap fraction and changes in leaf area index (LAI).[5,9,13] More recently, Gao and Goetz[14] reported on results of a study to retrieve EWT and biochemical information on vegetation canopies from AVIRIS data. Their approach focused on use of non-linear and linear least squares spectrum-matching techniques utilizing known spectra from endmembers such as liquid water, lignin, and cellulose to develop estimates of approximate absorption coefficients for the endmembers. These data were then utilized with similar data derived from the AVIRIS atmospherically corrected spectrum to solve for the endmember abundance vectors. Results of their least squares procedure for estimating EWT and lignin are similar to results obtained utilizing stepwise regression techniques with correlation coefficients reported in the 0.70 to 0.80 range.

Peterson, et al.[15] and Card et al. [5] described attempts to remotely sense biochemical constituents of leaves and forest canopies utilizing the visible and infrared regions of the spectrum. These authors focused on stepwise linear regression techniques to describe relationships between leaf chemical concentrations and reflectance data. In the laboratory, using dried samples, these methods produced results that compared reasonably well with error rates for wet chemical analysis techniques. Statistically significant regressions were demonstrated for protein, starch, sugar, lignin, nitrogen, total chlorophyll and cellulose. Success of the approach using field based data was limited by the increased variability attributed to changes in leaf area index, changes in leaf moisture content, canopy gap and the presence of other interferences. Card et al. [5] state that associating chemical bonds with certain wavelengths through regression techniques should be viewed with caution. The wavelengths selected by stepwise regression depend on the sample chosen, the mathematical transformations selected, and other factors. As sample size increases, the set of chosen wavelengths may become more consistent. In addition, selected wavelengths will not always occur precisely at known stretching frequencies because peak broadening and shifting can occur in leaves containing several constituents, each with a number of absorption peaks.

The objectives of this study were to continue evaluations of the "optimal passive *ambient* correlation spectroscopy" (OPACS) [16,17,18] method for analysis of high resolution spectral reflection signatures of vegetation. The target biophysical parameters were percent moisture, water status, chlorophyll, and total Kjeldahl nitrogen (TKN) for three dominant vegetation species present in the Florida subtropical scrub community. The three species were sand live oak (*Quercus geminata*), myrtle oak (*Q. myrtifolia*) and saw palmetto (*Serenoa repens*). These species are dominant members of an evergreen scrub community in the southeastern United States and are of vital importance to the survival of several federally listed threatened and endangered species of wildlife in Florida.

3. BACKGROUND

Optimal passive ambient correlation spectroscopy represents a powerful yet simple approach for the quantitative assessment of spectral signatures.[16,17,18] The process utilizes an optimal band selection methodology, based on a nonlinear 2nd derivative estimator, to define spectral regions of absorption or backscatter that can be utilized in biophysical parameter estimation. The approach produces an estimate of an analytical solution of the second derivative with respect to wavelength of the complex radiative transfer based equations for reflectance, thus directly estimating providing information on $d^2R/d^2\lambda$. In remote sensing, the first derivative or slope is commonly utilized to estimate biophysical parameters by incorporation of simple band ratio techniques. The second derivative or inflection can be viewed as a more precise measure of actual absorption or relative backscatter spectral regions, based on three or more bands. Inflection signatures are computed from reflectance signatures to develop three band optimal correlation estimates. The inflection estimator is defined as :

$$I(\lambda)_{m,i,n} = R^2(\lambda)_i \,/\, [R(\lambda)_{i-n} \times R(\lambda)_{i+m}] \tag{1}$$

where $I(\lambda)$ is the inflection or second derivative estimator centered at band (i) calculated from the reflectance signature. M and n are forward and backward operators, respectively.[16,20] The optimal channels located at m,i,n are determined by computing all combinations of m,i,n ranging from $i = 2\text{-}251$, $m = 2\text{-}252$, and $n = 1\text{-}250$. This nonlinear 2nd derivative can also be expressed in more simple terms as a ratio of two ratios:

$$I(\lambda)_{m,i,n} = [R(\lambda)_i / R(\lambda)_{i-n}] \,/\, [\, R(\lambda)_{i+m} / R(\lambda)_i] \tag{2}$$

For each combination of m,i,n, for a given set of reflectance signatures and biophysical estimators a linear regression is performed. Three band wavelength combinations which provide the maximum correlation coefficient are objectively defined as the optimum bands. A correlation spectrum can then be generated based on the maximum correlation obtained at each individual wavelength (i) providing insight into relative absorption and backscatter regions.

To further optimize the band selection procedure, an "optical clean up" of the spectrum can be performed by developing a ratio between the optimal bands for one biophysical feature and then selecting a second set of optimal bands. One example of this procedure is to compute this double inflection ratio (DIR): [16,17,18]

$$DIR(\lambda) = \{R^2(\lambda)_i \,/\, [R(\lambda)_{i-n} \times R(\lambda)_{i+m}]\} \,/\, \{R'^2(\lambda)_i \,/\, [R'(\lambda)_{i-n} \times R'(\lambda)_{i+m}]\} \tag{3}$$

where $R'(\lambda)$ represents the first set of optimized inflection channels and $R(\lambda)$ represents the second set of optimized inflection channels. This approach to optical clean up has been shown to be useful in aquatic remote sensing application related to separation of chlorophyll and suspended sediment signatures.[18] The technique is based upon an objective differential spectroscopy method whereby relative absorption and backscatter spectral regions are detected utilizing second derivatives of the reflectance signatures. As with the inflection estimator, the DIR can also be considered a ratio of ratios that are representative of the complex second derivative solution of the radiative transfer based equations for reflectance.[16]

4. METHODS

All high resolution spectral signatures were collected at Kennedy Space Center (KSC) Florida using two SE590 special high sensitivity solid state spectrographs with 252 channel linear diode arrays. Each channel samples approximately 3 nm over the range 386 to 1115 nm. An environmental optics chamber system with a barium sulfate reflectance coating was designed and constructed to measure leaf transmittance and reflectance utilizing a halogen light source. Each end of the optical chamber system was outfitted with SE590 spectrographs allowing simultaneous determination of leaf reflection and transmission. For each of four sample periods in March 1994, duplicate leaf samples were collected at KSC from two areas in the plant canopy of both *Q. geminata* and *Q. myrtifolia*. One pair was extracted from an area exposed to full sunlight and one pair was from full shade. The leaves were excised from the stems of individual plants with a scalpel to ensure a clean cut of the petiole for observation of response to application of a Scholander pressure bomb.[20] After collection, one leaf was immediately placed in the optical environmental test chamber where reflected and transmitted light were measured. The leaf was then cut in half, thickness was measured and it was placed in liquid nitrogen and stored frozen for future biochemical analyses. The second leaf was placed in the Scholander pressure bomb for measurement of water potential. Thus, for each of the sample periods, data were generated on water potential, spectral reflectance, transmittance and calculated absorptance signatures. These data were then subjected to OPACS analysis to develop empirical relationships between optimal wavelengths and simple estimates of water status as defined by pressure bomb readings.

In the field phase of the study during 1994 and 1995, canopy level spectral reflectance signatures for sand live oak, myrtle oak and saw palmetto at two locations were collected every 10-20 days for five sample periods between March and May 1994 and March and May 1995. All spectral signatures were collected in a random near nadir fashion from a distance of approximately 1-1.5 m above the targets, providing individual samples from an area of about 8-12 cm^2. For each collection, 20 replicate scans were obtained and the average spectral reflectance signature was computed. Upwelling light from the canopy was normalized to spectral signatures obtained from a calibrated dark Spectralon reflectance panel. Measurements were made at the same instrument gain and integration time. These signatures were used in the OPACS analysis.

All field samples were collected during full sunlight in morning hours at a time that corresponded to a solar elevation of 55-60 degrees, thus minimizing the influence of changing incidence angle on estimates of spectral signatures.[20,21] For each of the oak species, leaf samples were collected for determination of plant water potential (MPa) as indicated by Scholander pressure bomb estimates of the balance point[22] and measurement of percent moisture by low temperature drying in an oven at 80 C° for a minimum of 48 hours. During 1995, sampled dried leaves were ground and analyzed for TKN. In addition, for each 1995 sample period, leaf material from the canopy surface was processed for estimation of total chlorophyll concentration. Sub-samples of leaves were weighed, measured for leaf area, freeze dried, ground and chlorophyll a and b were extracted with acetone for 1.5 hours. Chlorophyll concentrations were determined using standard spectrophotometric procedures (Levine, pers. com.). Results were expressed as weight per unit area of leaf material. ($\mu g/cm^2$)

Natural scrub communities along the east central Florida coast occur on an undulating topography that is described as a ridge and swale system created as relict sand dunes associated with the historic rise and fall in sea level.[23] One field canopy sample site was established adjacent to a wetland in an area where average depth to the water table was approximately 0.5 m. The second sample site was located on a sand ridge system where depth to the water table was about 1.5 m. Soils in the upland area are classified as Pomello sand, and soils adjacent to the wetland are classified as Immokalee sand.[29] Selection of the two sites was made to represent variability in soil moisture available to the plants, a possible contributing factor to leaf water potential.[20] Depth to water table at each site was monitored throughout the study period through the use of shallow groundwater wells. Rainfall frequency and volume were also noted throughout the study.

Measurements were made at the canopy level throughout the spring period of leaf senescence, drop, sprouting and maturation in 1994 and 1995 to document changes in reflectance as a function of wavelength (λ) that may occur during this period of phenological transition. Gates[24], Sinclair et al.[25], Gausman et al.[26], and Boyer et al.[27] report that changes in leaf reflectance signatures during these transition periods can be attributed to changes in chlorophyll, other pigment concentrations and changes in the relative abundance and distribution of refractive interfaces within the leaf as the leaf changes shape, expands and matures.

5. RESULTS AND DISCUSSION

The primary objective of this study was to evaluate the potential for utilizing the OPACS procedure for definition of optimal bands or combinations of bands that could prove useful in developing remote estimates of biophysical characteristics of plants with future emphasis on applications to hyperspectral remote sensing data collected from aircraft and satellites. Figure 1 presents the reflectance signatures of leaves measured in the laboratory environmental optics chamber system that allows simultaneous collection of leaf reflected and transmitted light. Note that the signal becomes very noisy at the upper and lower wavelength regions of the measurement range. This is attributed to the lower output of the halogen

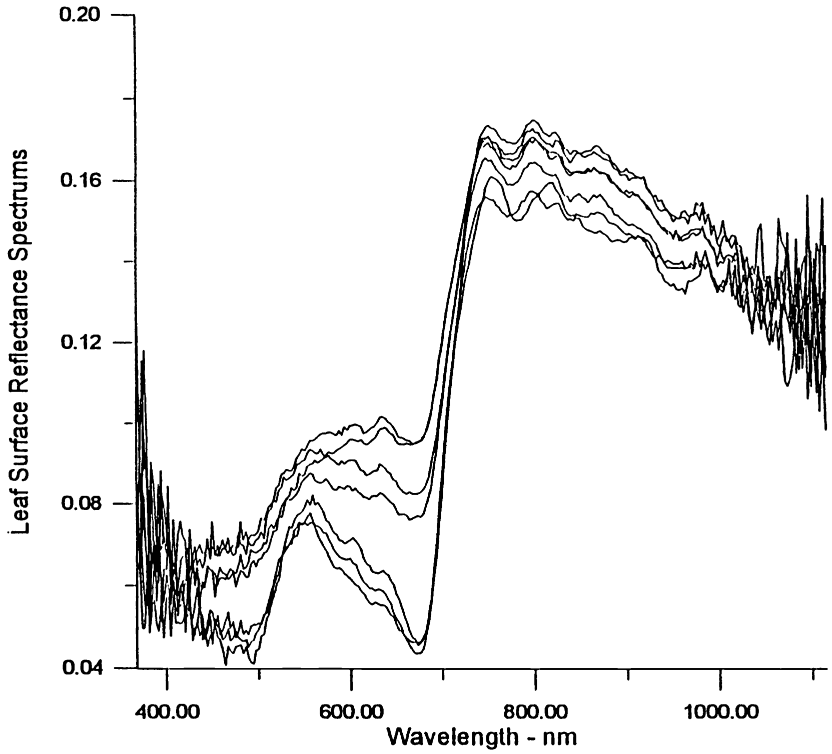

Figure 1. Mean reflectance signatures (n=5) for sand live oak and myrtle oak leaves analyzed in the environmental optics chamber during March 1994. Samples were collected to represent the range of variability of leaf senescence.

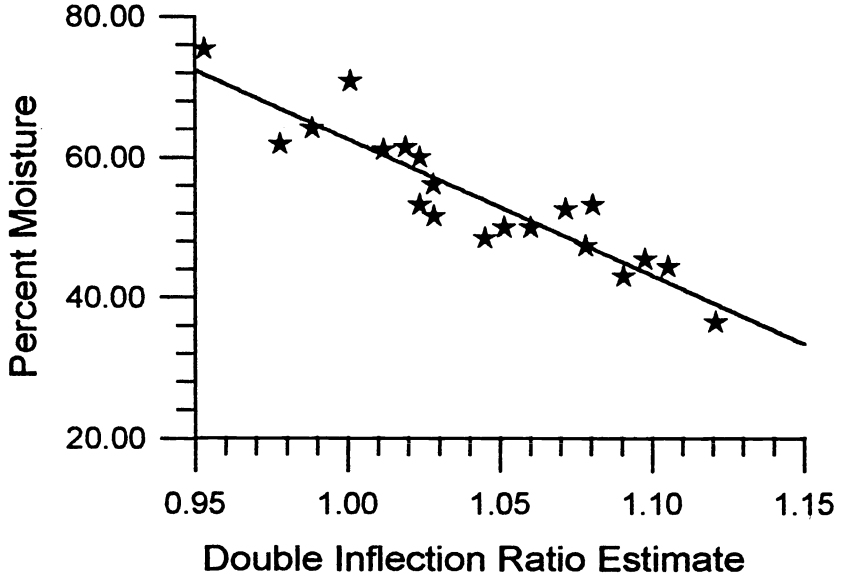

Figure 2. Linear relation between percent moisture of leaves from sand live oak and myrtle oak in 1994 and a double inflection ratio estimated using six channels. Wavelengths utilized were 861, 937, and 953 nm in the denominator and 947, 956, and 1051 nm in the numerator (n=20, r=-0.91).

light source at these wavelengths. The seven leaves shown in this figure were collected in March 1994, representing the range of senescence stages that can produce distinctively different leaf as well as canopy signatures. All of the leaves sampled were green in color with no blemishes or signs of insectivore. These oak species are virtual evergreens and they are never without some green leaf material in their canopies. Some leaves, late in the senescence process were stiff and brittle with age, while others were flexible and pliable at the time of sampling.

The degree of senescence is apparent in the reflectance signatures shown in Fig. 1. Leaves in the early stages of senescence displayed distinct reflectance maximum at 560-570 nm in a region that indicates the presence of chlorophyll and carotenoid pigments. For these leaves there is a distinct reflectance minimum at the base of the red shoulder near 680 nm in the vicinity of the second absorption maxima for chlorophyll a and b.[27] For all samples there is a dramatic increase in reflectance in the 690-740 nm region that is the result of enhanced light scattering within the leaf structure. Leaves further along in the senescence process display an increased reflectance in the 650 nm region, possibly as a result of increased anthocyanin development and reduced moisture altering leaf structure. In the near-infrared portion of the spectrum there appear to be slight absorption bands at about 775, 825 and 950 nm that correspond to identified water status correlation regions.[8,9]

Figure 2 presents results of an OPACS derived linear relationship computed using the DIR algorithm between leaf percent moisture and reflectance signatures for oaks (n=20) sampled in 1994. The coefficient of correlation was $r = -0.91$ for the relation between percent moisture and the six channel double inflection ratio. The six optimal bands were 861, 937 and 953 nm in the denominator and 947, 956 and 1051 nm in the numerator. The bands defined as optimal, based on the OPACS technique, correspond closely to the known water absorption bands in the near-infrared region suggesting a strong biophysical (absorption) basis for the spectral bands selected.

Examples of canopy level measurements of reflectance signatures for sand live oak collected over the two years are shown in Figs. 3 to 5. Between late March and May, the oak species were passing through a phenological transition where senescing leaves were falling to the ground as litter and new leaf material was being added rapidly to the canopy. Saw palmetto displayed no obvious changes in leaf characteristics during this period. Canopy level spectral signatures for sand live oak, myrtle oak and saw palmetto show that major changes in reflectance signatures are expressed in the near-infrared with a general trend of increasing reflectance over time. This general increase results from a combination of factors including effects of leaf level structural changes and increases in reflecting surfaces within new mature leaves [24,29] and the changing LAI and canopy biomass as the growing season progresses with a corresponding decrease in the proportion of soil and litter reflectance. In the visible portion of the spectrum, there are temporal changes in reflectance signatures that are associated with the changing ratios and amounts of chlorophyll, carotinoid and anthocyanin pigments in the leaves. These signals are also influenced by soil and leaf litter reflectance in sparse canopy situations. This was especially obvious for myrtle oak at the wetland site during 1995. High groundwater levels (depth = 0-10 cm) throughout the winter and spring produced extreme vegetation stress in the sample area and many nearby trees were dead or dying and canopies were sparse.

Results from the OPACS analysis between leaf water status indicators (percent moisture and water potential measurements) for canopy level measurements are presented in Figs. 6 and 7. Figure 6 shows results of the band selection analysis between leaf percent moisture and the reflectance spectra based on the single inflection three channel algorithm. The correlation coefficient was $r = 0.58$. The three optimum bands were 934, 997, and 1041. The relatively low correlation obtained is thought to be a result of several factors. The samples include saw palmetto, a species with highly rigid and fibrous long lived leaves that may not respond internally to changing water content and turgidity in the same fashion as the oak species, increasing variance in the data set. Also, the data set in the second year suffered from sparse leaf coverage due to a high water table.

Results of the OPAC analysis on water potential produced a correlation of $r = 0.79$ for the oak species (Fig. 7). The optimal bands for the dataset were 759, 926 and 1050 indicating a broad based response between increasing water potential and the second derivative of near-IR reflectance. Examination of the correlation spectra for a more focused response region or set of bands revealed a high correlation ($r = 0.77$) between inflection and water potential based on curvature behavior in the 783, 789 and 807 wavelength region, a known water absorption region.

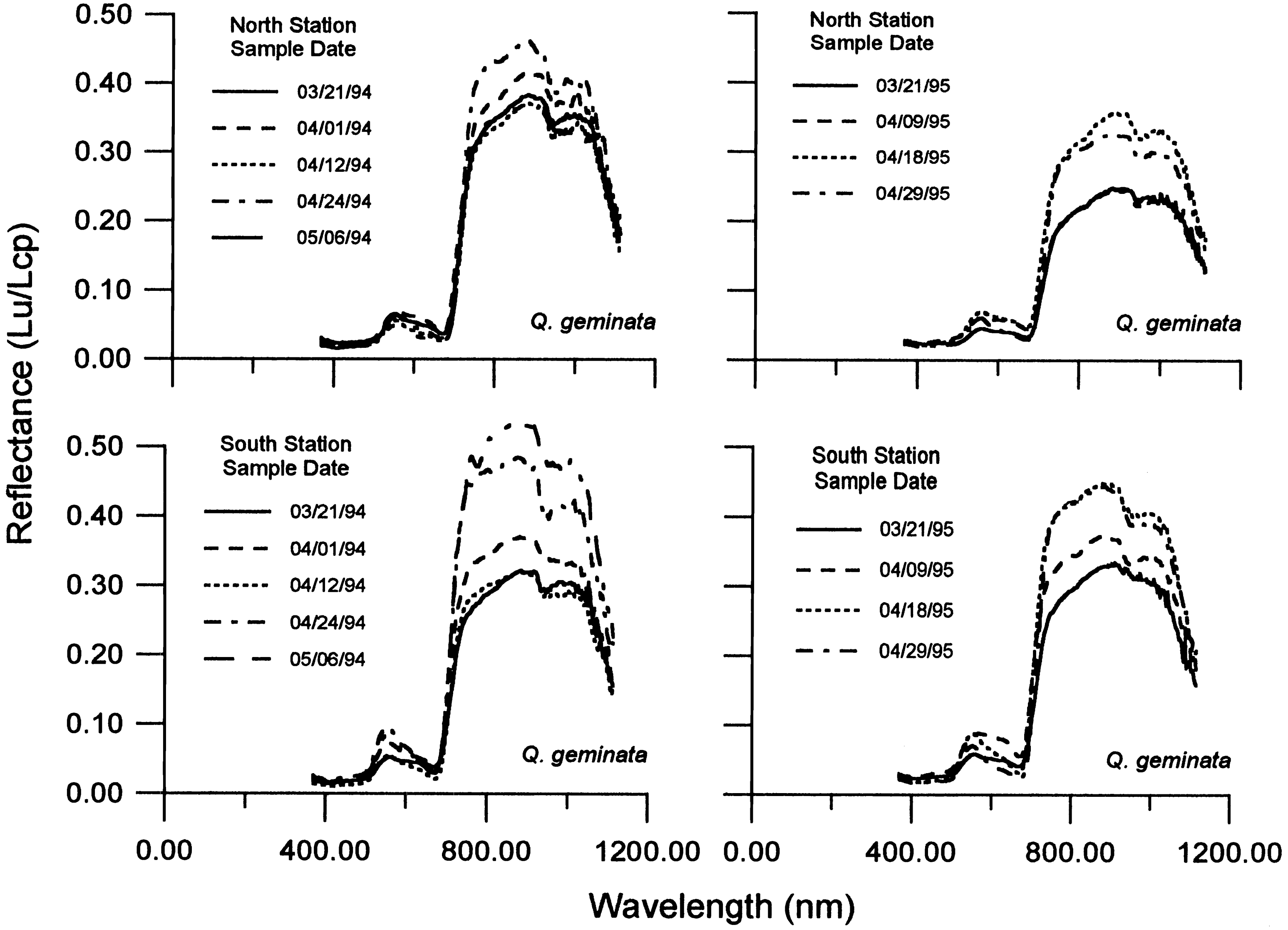

Figure 3. Mean spectral reflectance measurements (n=20) for sand live oak *(Quercus geminata)* collected from two sites during spring of 1994 and 1995. The north site was located adjacent to a wetland and the south site was located on a well drained sand ridge.

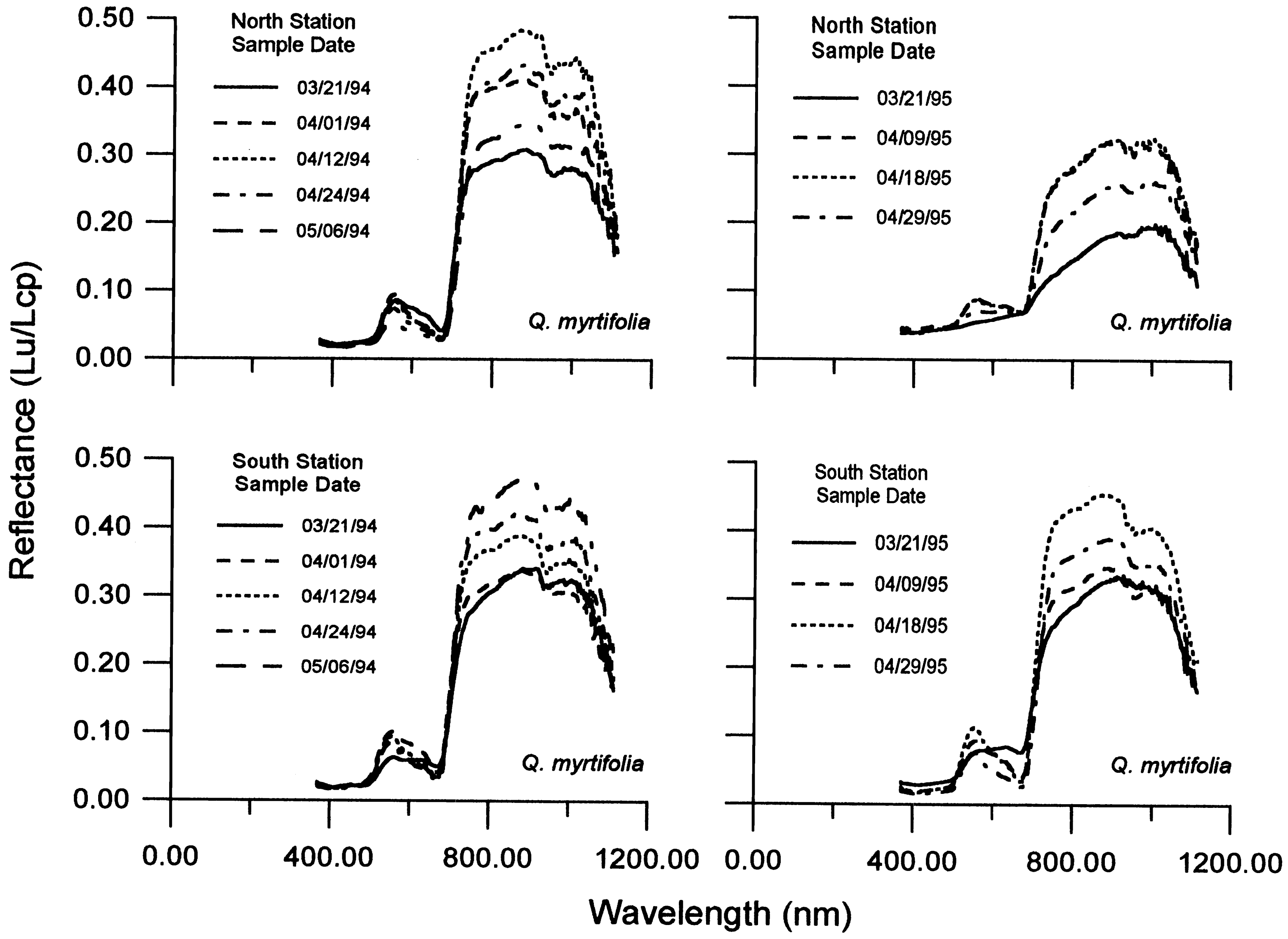

Figure 4. Mean spectral reflectance measurements (n=20) for myrtle oak *(Quercus myrtifolia)* collected from two sites during spring of 1994 and 1995. The north site was located adjacent to a wetland and the south site was located on a well drained sand ridge.

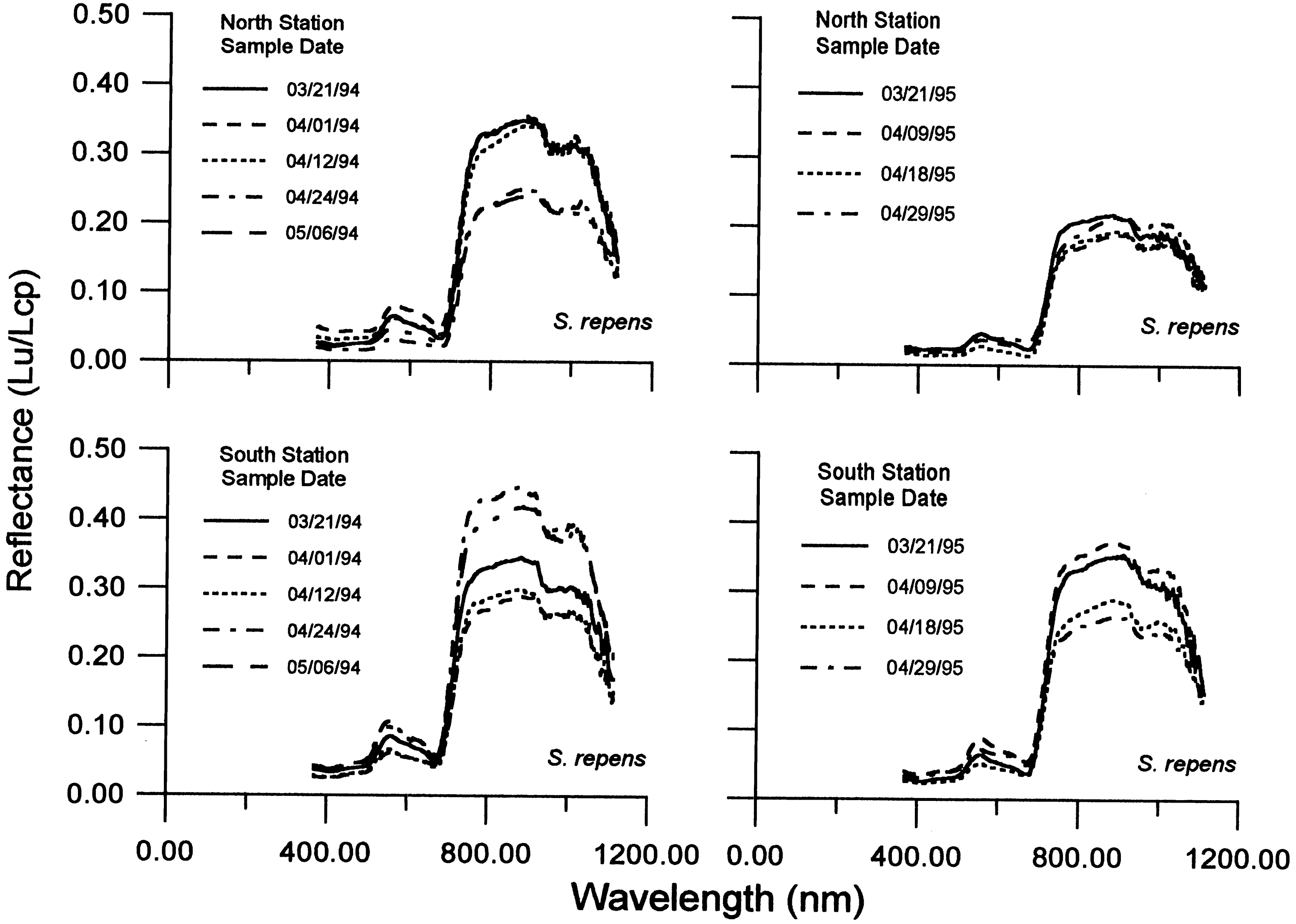

Figure 5. Mean spectral reflectance measurements (n=20) for saw palmetto *(Serenoa repens)* collected from two sites during spring of 1994 and 1995. The north site was located adjacent to a wetland and the south site was located on a well drained sand ridge.

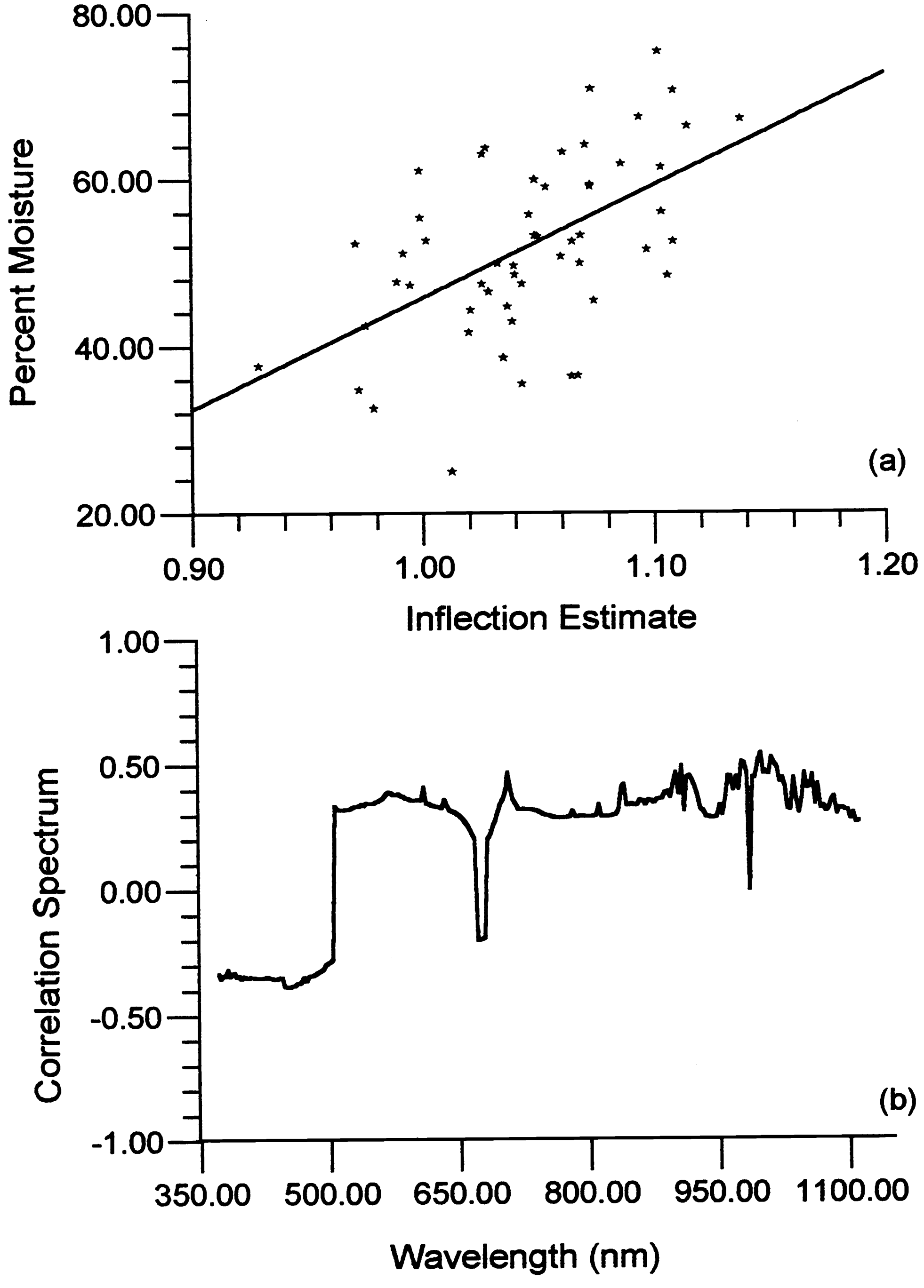

Figure 6. Estimated relationship between percent moisture measurements of three species of plant leaves and the 2nd derivative inflection estimates using three channels centered at 934, 997, and 1041 nm (n=54, r=0.58) and b) maximum correlation spectrum based on OPACS analysis.

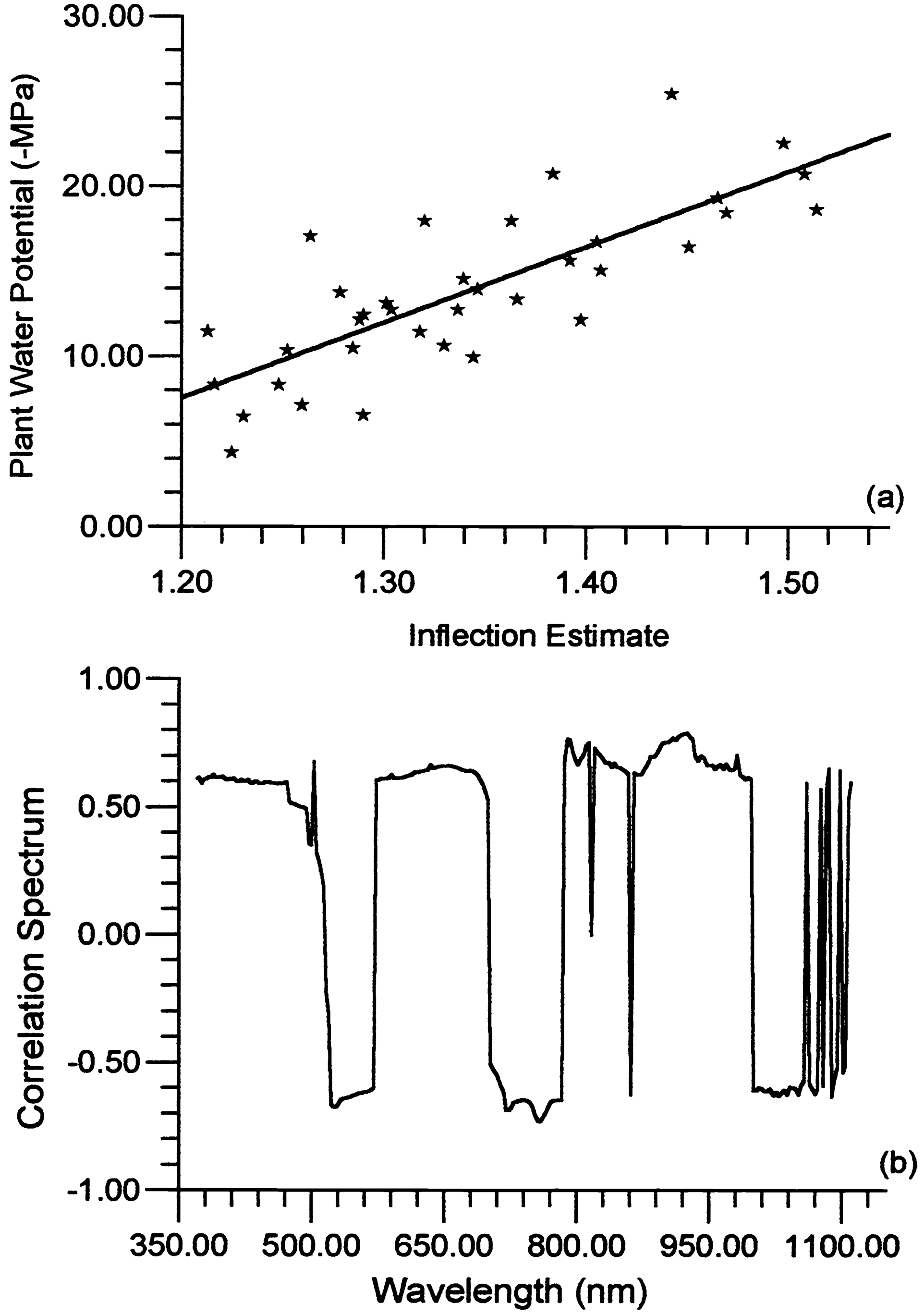

Figure 7. Estimated relationship between plant water potential measurements of two oak species and the 2nd derivative inflection estimates using three channels centered at 759, 926, and 1050 nm (n=36, 7=0.79) and b) maximum correlation spectrum based on OPACS analysis.

Results of the OPAC analysis for total chlorophyll are presented in Fig. 8. The optimal bands were defined as 641, 697, and 1079 nm with a correlation of r = -0.81. The inflection point at 697 nm corresponds to the area of maximum chlorophyll absorption in the red region of the spectrum at the base of the red edge. This same region was identified by Card et al.[5] utilizing multiple regression techniques with the second derivative of the spectral signal (r = 0.82) of dried ground leaf material. Results of TKN analysis in general displayed weak correlation to the inflection estimates with most values below r = 0.70. The optimal bands were defined as 947, 1022, and 1088 nm with a correlation of r = 0.81. Card et al., found stronger relationships between total nitrogen and the visible (580 and 480 nm) wavelengths (r = 0.95) utilizing multiple regression techniques on spectra of dried ground leaf material. It was speculated that the nitrogen was associated with chlorophyll and other pigment proteins.[5] Examination of the correlation spectra for TKN revealed the presence of two additional absorption regions with relatively strong associations to the inflection estimator. One region (r = 0.78) was defined by the 789, 845, 883 nm wavelengths while the second region (r = 0.72) corresponded to the 460, 466, 486 nm wavelengths. It is speculated that this second region may be associated with the nitrogen found in chlorophyll or other plant pigments.

6. SUMMARY

From the results obtained in this study it appears that the optimum bands selected are associated with reflectance inflection or spectral curvature located in biophysical based absorption or backscatter regions. The unique nature of the OPACS procedure with its' strong basis in radiative transfer theory[16] suggests that it is an objective approach for quantitatively analyzing and interpreting high resolution spectral signatures. More detailed evaluations of optical cleanup procedures need to be conducted as well as special data collection studies to address sources of variance in the reflectance signal such as changing LAI, canopy gap, and influences of leaf litter and soils. Further testing and development in a larger variety of landscape types and situations, including application to high spectral resolution data derived from aircraft and satellites is needed to continue refining and testing the applicability of the OPACS procedure and the bands or spectral regions identified in this study for estimating biophysical parameters based on absorption and backscatter regions.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. G. Vane and A. F. H. Goetz. "Terrestrial imaging spectrometry: current status, future trends, " Remote Sens. Environ. 44:117-126, 1993.

2. G. Foody and P. Curran. (Eds) Environmental remote sensing from regional to global scales. John Wiley & Sons. New York, 1994.

3. R. J. Hoobs and H. A. Mooney. (Eds) Remote sensing of biosphere functioning. Springer-Verlag. New York, 1989.

4. C. A. Wessman. "Evaluation of canopy biochemistry,". In: J. H. Hobbs and H. A. Mooney. (Eds) Remote sensing of biosphere functioning. Springer-Verlag, New York, 135-156, 1989.

5. D. H. Card, D. L. Peterson, and P. A. Matson. "Prediction of leaf chemistry by the use of visible and near infrared reflectance spectroscopy," Remote Sens. Environ. 26:123-147, 1988.

6. E. R. Hunt Jr., B. N. Rock, and P. S. Nobel. "Measurement of leaf relative water content by infrared reflectance," Remote Sens. Environ. 22:429-435, 1987.

7. E. R. Hunt Jr. and B. N. Rock. "Detection of changes in leaf water content using near- and middle infrared reflectances," Remote Sens. Environ. Remote Sens. Environ. 30:43-54, 1989.

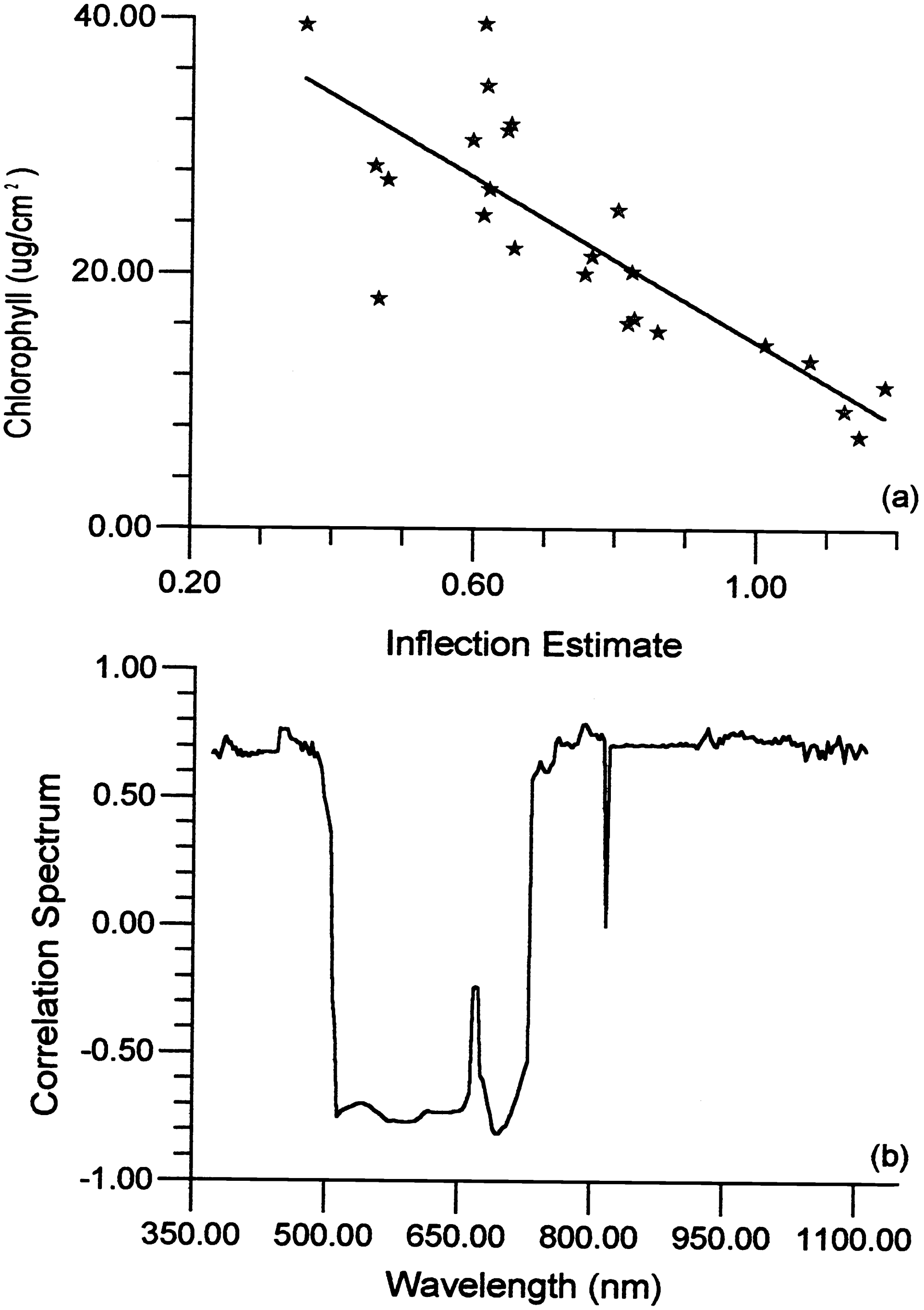

Figure 8. Estimated relationship between chlorophyll measurements of three species of plant leaves and the 2nd derivative inflection estimates using three channels centered at 641, 697, and 1079 nm (n=24, r=-0.81) and b) maximum correlation spectrum based on OPACS analysis.

8. W. D. Bowman. "The relationship between leaf water status, gas exchange and spectral reflectance in cotton leaves," Remote Sensing of the Environment, 30:249-255, 1989.

9. J. Penuelas, I. Fiella, C. Biel, L. Serrano, and R. Save. "The reflectance at the 950-970 nm region as an indicator of plant water status," Int. Journal Remote Sens. 14:1887-1905, 1993.

10. Bo-Cai Gao and A. F. H.Goetz. "Extraction of dry leaf spectral features from reflectance spectra of green vegetation," Remote Sens. Environ. 47:369-374, 1994.

11. J. R. Thomas, L. N. Nemken, G. F. Oerther, and R. G. Brown. "Estimating leaf water content by reflectance measurements," Agronomy Journal 63:845-847, 1971.

13. R. E. Hunt, Jr. and S. W. Running. "Problems with scaling leaf water relations to regional scales," University of Montana In: Proc. of IGARSS, 1990.

14. Bo-Cai Gao and A. F. H. Goetz. "Retrieval of equivalent water thickness and information related to biochemical components of vegetation canopies from AVIRIS data," Remote Sens. Environ. 52:155-162, 1995.

15. D. L. Peterson, J. D. Aber, P. A. Matson, D. H. Card, N. Swanberg, C. Wessman, and M. Spanner. "Remote sensing of forest canopy and leaf biochemical contents," Remote Sens. Environ. 24:85-108, 1988.

16. C. R. Bostater, W. Ma, and A. Lamb. "Simulating radiative transfer in aquatic systems and contrasting results from ambient environmental spectroscopy: estuarine and near coastal waters," Proceedings of the International Symposium on Spectral Sensing Research. R. B. Gomez (Ed). Volume II, 673-679. San Diego, 1994.

17. Bostater, C. R., Hall, C. R., Vieglais, D., Rebbman, J., and M. J. Provancha. "Temporal measurements of high resolution spectral signatures of plants and relationships indicating water status." Proceedings of the International Symposium on Spectral Sensing Research. R. B. Gomez (Ed). Volume I, 387-402. San Diego, 1994.

18. C. R. Bostater. "Remote sensing methods using aircraft and ships for estimating optimal bands and coefficients related to ecosystem responses," Proceedings of the First Thematic Conference on Remote Sensing for Maine and Coastal Environments. New Orleans, La. 1992.

19. G. Grew. "Real-time test of MOCS algorithm during superflux 1980," Chesapeake Bay Plume Study, Superflux 1980, NASA Pub. 2188, Washington, D. C., 301-322, 1980.

20. P. J. Kramer. Water relations of plants, Academic Press, New York, 489 pp. 1983.

21. G. A. Riggs and S. W. Running. "Detection of canopy water stress in conifers using the airborne imaging spectrometer," Remote Sens. Environ. 35:51-68, 1991.

22. M. T. Tyree and H. T. Hammel. "The measurement of the turgor pressure and the water relations of plants by the pressure-bomb technique," Journal of Experimental Botany, 23:267-282, 1972.

23. P. A. Schmalzer and C. R. Hinkle. "Geology, geohydrology and soils of Kennedy Space Center: a review," NASA Technical Memorandum 103813. John F. Kennedy Space Center, Fl. 1990.

24. D. M. Gates. Biophysical Ecology. Springer-Verlag, New York. 611 pp. 1980.

25. T. R. Sinclair, M. M. Screiber, and R. M. Hoffer. "Reflectance and internal structure of leaves from several crops during a growing season," Agronomy Journal, 63:864-868, 1971.

26. H. W. Gausman, W. A. Allen, R. Cardenas, and A. J. Richards. "Relationships of light reflectances to histological and physical evaluations of cotton maturity (*Gossypium hirsutum, L.*)," Applied Optics, 9:545-552, 1970.

27. M. Boyer, J. Miller, M. Belanger, and E. Hare. "Senescence and spectral reflectance in leaves of northern pin oak (*quercus palustris* Muenchh.)," Remote Sens. Environ. 25:71-87, 1988.

28. L. Grant. " Diffuse and specular characteristics of leaf reflectance," Remote Sens. Environ. 22:309-322, 1987.

29. H. Huckle, D. Dollar, and R. Pendleton. Soil Survey of Brevard County, Florida, U. S. Department of Agriculture, Soil Conservation Service. Washington D.C. 123 p. 1974.