A MULTI-SCALE SAMPLING STRATEGY FOR DETECTING PHYSIOLOGICALLY SIGNIFICANT SIGNALS IN AVIRIS IMAGERY

John A. Gamon[1], Lai-Fun Lee[1], Hong-Lie Qiu[2]
[1]Department of Biology and Microbiology
[2]Department of Geography and Urban Analysis
California State University, Los Angeles
Los Angeles, CA 90032

Stephen Davis
Natural Science Division
Pepperdine University
Malibu, CA 90263

Dar A. Roberts
Department of Geography
University of California, Santa Barbara, CA 93106

Susan L. Ustin
Department of Land Air and Water Resources
University of California, Davis, CA, 95616

1. INTRODUCTION

Models of photosynthetic production at ecosystem and global scales require multiple input parameters specifying physical and physiological surface features. While certain physical parameters (e.g., absorbed photosynthetically active radiation) can be derived from current satellite sensors, other physiologically relevant measures (e.g., vegetation type, water status, carboxylation capacity, or photosynthetic light-use efficiency), are not generally directly available from current satellite sensors at the appropriate geographic scale. Consequently, many model parameters must be assumed or derived from independent sources, often at an inappropriate scale (Hall et al. 1995, Sellers et al 1995).

An abundance of ecophysiological studies at the leaf and canopy scales suggests strong physiological control of vegetation-atmosphere CO_2 and water vapor fluxes, particularly in evergreen vegetation subjected to diurnal or seasonal stresses. For example hot, dry conditions can lead to stomatal closure, and associated "downregulation" of photosynthetic biochemical processes, a phenomenon often manifested as a "midday photosynthetic depression" (Tenhunen et al. 1984, 1985 and 1990). A recent study with the revised simple biosphere (SiB2) model demonstrated that photosynthetic downregulation can significantly impact global climate (Sellers et al. 1996). However, at the global scale, the exact significance of downregulation remains unclear, largely because appropriate physiological measures are generally unavailable at this scale (Prince et al. 1995, Sellers at al. 1996). Clearly, there is a need to develop reliable ways of extracting physiologically relevant information from remote sensing.

Narrow-band spectrometers offer many opportunities for deriving physiological parameters needed for ecosystem and global scale photosynthetic models. Experimental studies on the ground at the leaf- to stand- scale have indicated that several narrow-band features can be used to detect plant physiological status. One physiological signal is caused by xanthophyll cycle pigment activity, and is often expressed as the Photochemical Reflectance Index (PRI; Gamon et al. 1992, 1997; Peñuelas et al. 1995, 1997). Because the xanthophyll cycle pigments are photoregulatory pigments closely linked to photosynthetic function (Demmig-Adams and Adams 1996), this index can be used to derive relative photosynthetic rates (Gamon et al. 1997). An additional signal with physiological significance is the 970 nm water absorption band, which provides a measure of liquid water content (Peñuelas et al. 1993, 1997; Zhang et al. 1997; Sanderson et al. in press). This feature has been quantified both using a simple 2-band ratio (900/970 nm, here referred to as the "Water Band Index" or WBI; Peñuelas et al. 1993, 1997), and using the "continuum removal" method (Clark and Roush, 1984, as cited in Zhang et al. 1997 and Sanderson et al. in press). Current atmospheric correction methods for AVIRIS imagery also obtain quantitative expressions of surface liquid water absorption based on the 970 nm water band (Green et al. 1993, Roberts et al. 1997) and may be comparable to ground-based estimates of water content using this feature. However, physiological interpretations of both the PRI and the WBI are best understood at the leaf and canopy scales, where complications of atmospheric interference and complex stand and landscape features can be minimized, and where experimental manipulations can be readily applied.

Currently it is not known whether these physiological indices can be used to derive meaningful physiological information from AVIRIS imagery. In addition to the problem of atmospheric interference, another challenge is that any simple physiological index can be confounded by multiple factors unrelated to physiology, and this problem can become more severe at progressively larger spatial scales. For example, previous work has suggested that both the PRI (Gamon et al, 1995) and the WBI (Peñuelas et al, 1993, 1997), are strongly correlated with other optical measures of canopy structure (e.g., the Normalized Difference Vegetation Index or green vegetation fraction), indicating a confounding effect of structure on physiological signals at the larger, landscape scale. Furthermore, the normal operating mode of most imaging spectrometers does not allow simultaneous, ground truthing at a level of detail needed for physiological sampling. Additionally, manipulative experiments of physiology are difficult to apply at a geographic scale suitable for comparison with remote imagery, which often works at spatial scales that are several orders of magnitude larger than those typically used for physiological studies. These limitations require the consideration of alternative approaches to validating physiological information derived from AVIRIS data.

In this report, we present a multi-scale sampling approach to detecting physiologically significant signals in narrow-band spectra. This approach explores the multi-dimensional data space provided by narrow-band spectrometry, and combines AVIRIS imagery at a large scale, with ground spectral sampling at an intermediate scale, and detailed ecophysiological measurements at a fine scale, to examine seasonally and spatially changing relationships between multiple structural and physiological variables. Examples of this approach are provided by simultaneous sampling of the Normalized Difference Vegetation Index (NDVI), an index of fractional PAR interception and green vegetation cover (Kumar and Monteith 1981, Asrar et al. 1984, Hatfield et al. 1984, Sellers 1985, Bartlett et al. 1990, Gamon et al. 1995), the Water Band Index (WBI, an index of liquid water absorption; Peñuelas 1993 and 1997), and the Photochemical Reflectance Index (PRI, an index of xanthophyll cycle pigment activity and photosynthetic light-use efficiency; Gamon et al. 1992 and 1997, Peñuelas et al. 1995 and 1997). By directly linking changing optical properties sampled on the ground with measurable physiological states, we hope to develop a basis for interpreting similar signals in AVIRIS imagery.

2. METHODS

All ground measurements presented here were made in 1997 at the Malibu Forestry Unit (Los Angeles County Fire Department) site, near Tapia Park in the Santa Monica Mountains, California, USA. This site, which is normally dominated by chaparral vegetation, burned in October, 1996, and was in early stages of secondary succession during 1997. In this first year following the fire, the landscape was covered by a diversity of species, ranging from reseeding annuals and perennials, to resprouting, perennial chaparral shrubs.

Spectral reflectance was measured from the ground using a prototype spectrometer constructed from a silicon photodiode detector (Zeiss MMS1, NIR enhanced, with VIS blaze, Hellma Cells, Forest Hills, New York, USA), fitted with a single fiber optic probe (15-0600 LTS-T39-P-2-SMA/SP, General Fiber Optics, Inc, Fairfield, New Jersey, USA) fitted with a tube that restricted the field-of-view to approximately 18 degrees. Reflectance was sampled at each meter along three transects, varying from 50 to 100 meters in length and covering both north- and south-facing slopes. Spectra were measured from a distance of approximately 1 m from the surface, so that each spectrum sampled a ground or canopy area of approximately 0.1 m^2. Reflectance measurements were made on April 12 and 18 ("spring"), July 4 and 5 ("summer") and October 5 ("fall"). The spring and fall dates matched within a few days the dates of three AVIRIS overflights.

Reflectance indices were derived from reflectance spectra using the following formulas:

$$NDVI = (R_{750}-R_{660})/(R_{750}+R_{660}) \quad (1)$$

$$WBI = (R_{900}/R_{970}) \quad (2)$$

$$PRI = (R_{531}-R_{570})/(R_{531}+R_{570}) \quad (3)$$

where R_{XXX} represents reflectance at the indicated wavelength (XXX, in nm).

Leaf water status was sampled with a pressure chamber (model 1001, PMS Instrument Co., Corvallis, Oregon), and expressed as pre-dawn water potentials, a common physiological measure of seasonally changing plant water status (Koide et al. 1989). Water potential samples from *Adenostema fasciculatum* ("chamise") resprouts and seedlings and from *Ceanothus crassifolius* seedlings were averaged to create representative values for this site. Because water potential values were not sampled on the same dates as reflectance, we averaged values from the dates closest to the reflectance sampling for this analysis to estimate water status comparable to reflectance measurements (table 1).

AVIRIS data tapes for this site and dates were not obtained in time for these proceedings. Consequently, we conducted our analysis using previously available AVIRIS images of Point Dume from fall of 1994 (May 9) and spring of 1995 (October 19), that closely matched the spring and fall dates of ground sampling, but on different years and on different locations. These scenes were expressed as surface reflectance using the atmospheric correction method of Green et al. (1993). Spectral mixture analysis, conducted using a commercial software package (ENVI, Research Systems, Inc., Boulder, Colorado, USA), allowed us to select spectrally uniform regions representing distinct, uniform vegetation types (riparian and oak woodland, coastal sage scrub, chaparral, and annual grassland). The identity of these vegetation types was then confirmed with field visits. For each date and vegetation type, spectra and reflectance indices were then extracted from the two image cubes. Reflectance indices were derived by selecting the AVIRIS bands closest to the wavelength values indicated in equations 1-3, above.

3. RESULTS

The WBI was strongly correlated with NDVI for all three ground sampling dates (figure 1). In this figure, low NDVI values represent bare soil, and high values indicate complete vegetation cover. Further analysis using analysis of covariance (ANCOVA) indicated that the slope of this relationship changed significantly between April and June ($p < 0.001$), but not between June and October (figure 1B). Similarly, predawn water potentials declined significantly between April and June, but not between June and October (table 1). Plots of PRI vs. NDVI for the same dates yielded similar patterns, indicating significant changes in slope between spring and summer, but not between summer and fall (figure 2).

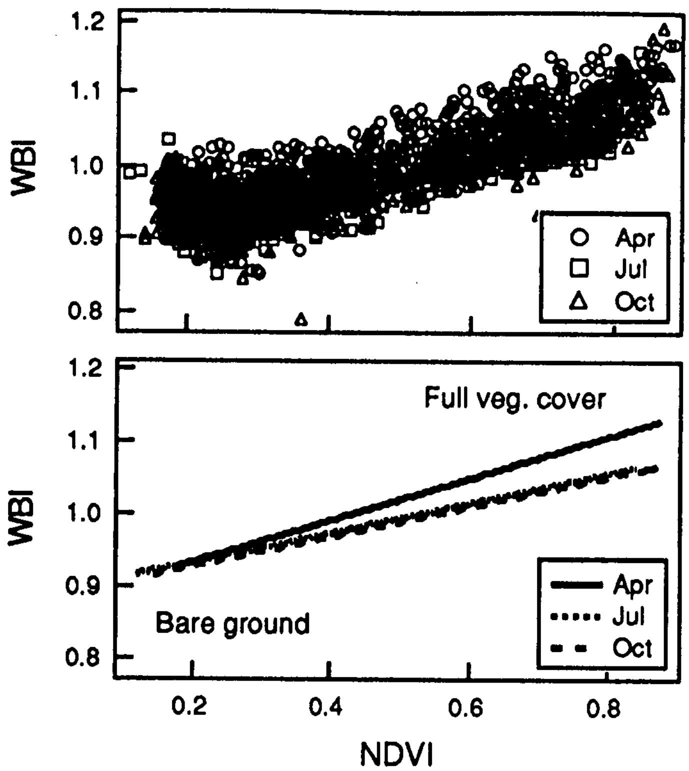

Figure 1. The Water Band Index (WBI) plotted against the Normalized Difference Vegetation Index (NDVI), both measured on the ground near Tapia Park, Santa Monica Mountains, California, in spring, summer, and fall, 1997. Each individual sampling point in panel A represents a surface area of approximately 0.1 m^2. Linear regressions (panel B) were highly significant ($p<0.0001$, Fisher's probability) and analysis of covariance indicated a significant change in slope between April and July, but not from July to October.

Date	mean Ψ (MPa)	SEM	range
April	-1.27	0.46	-0.40 to 3.32
July	-2.94	0.41	-2.13 to -3.19
October	-4.04	0.62	-1.75 to -5.14

Table 1. Mean, standard error of the mean (SEM), and range of predawn leaf water potential (Ψ) values near Tapia Park corresponding to the three reflectance dates in 1997. Mean values were estimated by averaging measurements of seedlings and resprouts of two species, as indicated in Methods. Lower values indicate drier leaves.

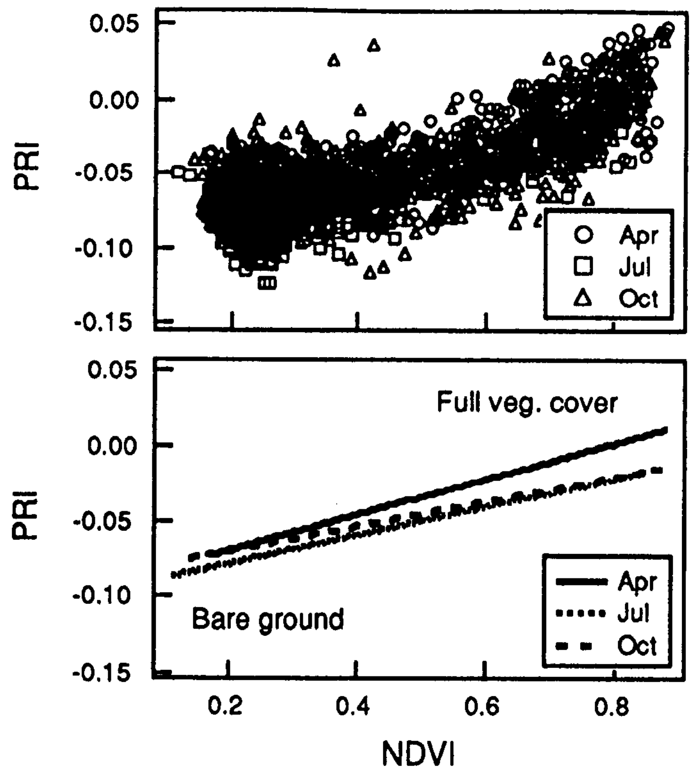

Figure 2. The Photochemical Reflectance Index (PRI) plotted against the Normalized Difference Vegetation Index (NDVI), both measured on the ground near Tapia Park, Santa Monica Mountains, California, in spring, summer, and fall, 1997. Each individual sampling point in panel A represents a surface area of approximately 0.1 m^2. Linear regressions (panel B) were highly significant ($p<0.0001$, Fisher's probability) and analysis of covariance indicated a significant change in slope between April and July, but not from July to October.

The plots of WBI vs. NDVI derived from AVIRIS are indicated in figure 3. As with the ground data, WBI was positively and strongly correlated with NDVI, and the relationship changed seasonally. For each vegetation type, both WBI and NDVI declined with the onset of summer drought, and this decline was most severe for the annual grassland and least severe for oak woodland. In contrast to these results, and in contrast to the pattern found on the ground (not shown), plots of PRI vs. NDVI derived from AVIRIS did *not* resemble the pattern found with the WBI. Unlike the results on the ground and in contrast to our expectations, the apparent PRI values derived from AVIRIS yielded a *negative* relationship with NDVI and *declined* from spring to fall (not shown).

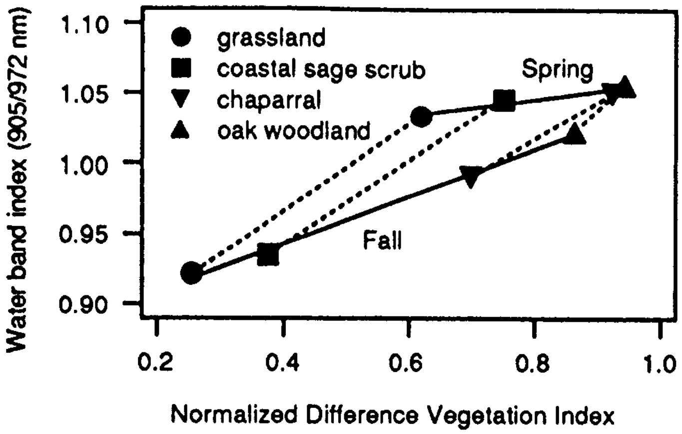

Figure 3. Values for the Water Band Index (WBI) vs. Normalized Difference Vegetation Index (NDVI) for different native vegetation types, derived from AVIRIS images of Point Dume (Santa Monica Mountains, CA). Each point represents the mean of 17 to 22 AVIRIS pixels (standard error bars are too small to see). Solid lines represent regression lines for samples selected from a single date in Spring, 1995 (top regression), or Fall, 1994 (bottom regression). Dashed lines represent hypothetical seasonal trajectories for each vegetation type in NDVI-WBI space.

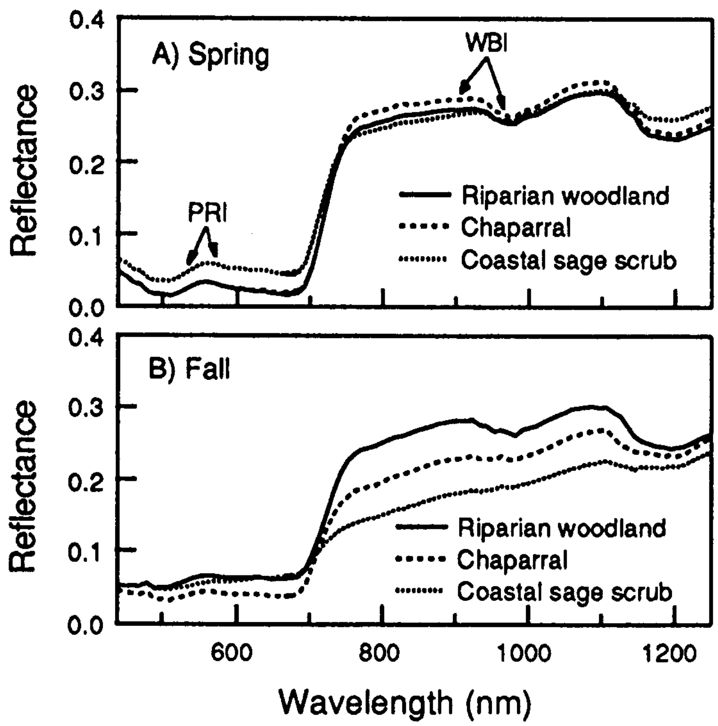

Figure 4. Apparent reflectance spectra for representative vegetation types derived from AVIRIS overflights of the Santa Monica Mountains, CA, in Spring, 1995 (panel A) and Fall, 1994 (panel B). Wavebands used for calculation of the Photochemical Reflectance Index (PRI) and the Water Band Index (WBI) are indicated on the top panel. Note aberrant patterns in apparent reflectance, particularly visible below 500 nm, which apparently confound accurate estimation of PRI for these scenes. Also, note the "flattening" of the 970 nm liquid water absorption feature from spring to fall, particularly for the drought-deciduous coastal sage scrub.

AVIRIS spectra for selected vegetation types are indicated in figure 4, along with the wavelengths used for calculation of the WBI and PRI. Note the "flattening" of the spectrum and concurrent loss of the 970 nm water absorption feature at the end of the summer drought, particularly for the drought-deciduous coastal sage scrub (compare 4A to 4B). Note also that the 400-550 nm region adjacent to PRI yields visibly distorted apparent reflectance spectra, visible as a steep slope in apparent reflectance (4A) or as small spikes in apparent reflectance (4B).

4. DISCUSSION

The finding of a positive relationship between the WBI and NDVI is consistent with several recent reports of a strong correlation between liquid water absorption and green canopy cover or leaf area as measured by NDVI (Peñuelas et al. 1997, Roberts et al 1997), or green vegetation fraction (Roberts et al. 1997, Ustin et al. in press). This suggests that the WBI is largely functioning as a measure of green canopy cover or leaf area index. However, the significant changes in the WBI for a given value of NDVI (figures 1 and 3) illustrate a component of the 970 nm water absorption feature that appears to be independent of canopy structure and more directly related to leaf water concentration. This conclusion is consistent with a number of recent reports that suggest changing leaf or canopy water content can be detected with this feature (Peñuelas et al. 1993, 1997; Zhang et al. 1997, Sanderson et al. in press). Seasonal patterns of leaf water potential gathered from single leaves on the ground (table 1) further support the hypothesis that the seasonal change in the WBI for a given NDVI indicates changing leaf water content. However, these leaf water potentials cannot provide a direct confirmation of this hypothesis for three reasons: 1) water potentials were not sampled on identical dates, canopies, or spatial scales as either ground or airborne reflectance sampling, 2) the units of water potential (pressure units, see Koide et al. 1989) are not linearly related to the units of liquid water content sampled with reflectance (more typically unitless, or expressed in microns of liquid water, see Roberts et al. 1997), and 3) the water potential samples were made before dawn, whereas AVIRIS flies near solar noon. Nevertheless, these preliminary results present qualitative support for the hypothesis that a component of the WBI and other similar measures of liquid water absorption (Roberts et al. 1997, Ustin et al. in press) is directly related to seasonally changing leaf water status. In mediterranean climate vegetation, where summer drought is a main factor limiting photosynthetic performance (Mooney et al, 1975, Tenhunen et al. 1984, 1985 and 1990, Gamon et al, 1995), this component of the WBI may have direct physiological relevance, and may provide a means to remotely assess changing photosynthetic function. Further work is required before we can derive quantitative expressions of leaf water status or physiological function from this index, and better quantitative expressions of vegetation water content may emerge.

Even in the absence of quantitative solutions, the water absorption bands visible in AVIRIS spectra could be quite useful. The tendency for different vegetation types to occupy distinct trajectories in NDVI-WBI space (figure 3) suggests that it might be possible to develop functional classifications of vegetated landscapes entirely from imaging spectrometry using this approach. Similar vegetation classifications have been obtained with NDVI and surface temperature derived from AVHRR data (Nemani and Running, 1997). To our knowledge, classification of vegetation based on the water absorption features is relatively unexplored.

The similarity of the PRI-NDVI to the WBI-PRI patterns sampled from the ground (compare figures 1 and 2) provides further evidence that seasonal water limitations reduce photosynthetic fluxes in this drought-prone landscape. The finding of a decline in PRI for a given NDVI with the onset of summer drought (figure 2) is consistent with an abundance of reports indicating that ground-based PRI sampling can provide a useful indicator of photosynthetic function (e.g., Gamon et al. 1992 and 1997, Peñuelas et al. 1995 and 1997, Filella et al. 1996). Furthermore, these transect samples traversing several AVIRIS pixels suggest that a meaningful PRI could be measured from AVIRIS if a good surface reflectance retrieval could be obtained. However, the same pattern of a seasonal decline in PRI for a given NDVI was not apparent in the AVIRIS imagery (not shown). Preliminary analyses suggest that radiometric or spectral calibration errors or insufficient atmospheric correction can lead to significant errors in PRI. In particular, atmospheric scattering was a likely source of error for these particular AVIRIS scenes due to a strong influence of marine aerosols. Complete atmospheric correction in this visible region of the spectrum remains a significant challenge, and is rarely attained without suitable ground calibration targets during the overflight

(Clark et al. 1993, Goetz et al., 1998). Simultaneous ground sampling during AVIRIS overflights could help solve this problem, but such simultaneous measurement is not always possible. Until this challenge can be resolved, PRI appears to be best sampled from close range where atmospheric interference is not a significant problem.

Because photosynthetic function and leaf water content are both very dynamic in time and space, and because physiological sampling and aircraft imaging spectrometry operate over vastly different spatial scales, it is extremely challenging to directly confirm any physiological interpretation AVIRIS reflectance spectra. Simultaneous sampling of reflectance at the stand scale from the ground would greatly help in confirming any quantitative interpretation of physiological signals derived from AVIRIS spectra. This would require closer coordination between AVIRIS flight crew and field sampling team, and a much larger investment of time and resources in field sampling than is usually the case. Extremely accurate spectral and radiometric calibration, and accurate retrieval of surface reflectance will also be essential for full evaluation of physiological signals in AVIRIS imagery. We are currently evaluating these issues with additional AVIRIS data from the Santa Monica Mountains.

5. ACKNOWLEDGMENTS

We wish to thank Meg Gardner (UC Santa Barbara) for assistance with atmospherically corrected AVIRIS scenes, Robert Green and Betina Pavri (Jet Propulsion Laboratory) for discussion of atmospheric correction methods, and Brandon Pratt and Kim Portwood for assistance with leaf water potential values. Access to the field site was provided by the Malibu Forestry Unit of the Los Angeles County Fire Department, and funding for the ground reflectance sampling was provided by the National Science Foundation. This is publication #3 of the Center for Spatial Analysis and Remote Sensing, California State University, Los Angeles, which is supported by funds from NASA.

6. REFERENCES

Asrar, G, M. Fuchs, E.T. Kanemasu, and J.L. Hatfield, 1984, "Estimating Absorbed Photosynthetic Radiation and Leaf Area Index from Spectral Reflectance in Wheat," *Agronomy Journal*. 76:300-306.

Bartlett, D.S., G.J. Whiting, and J.M. Hartman, 1990, "Use of Vegetation Indices to Estimate Intercepted Solar Radiation and Net Carbon Dioxide Exchange of a Grass Canopy," *Remote Sensing of Environment*. 30:115-128.

Clark, R.N., G. Swayze, K. Heidebrecht, A.F.H. Goetz, and R.O. Green, 1993, "Comparison of Methods for Calibrating AVIRIS Data to Ground Reflectance," *Summaries of the Fourth Annual JPL Airborne Geoscience Workshop*, October 25-29, 1993. 1:35-36.

Clark, R.N., and T.L. Roush, 1984, "Reflectance Spectroscopy: Quantitative Analysis Techniques for Remote Sensing Applications," *Journal of Geophysical Research* 89(B7):6329-6340.

Demmig-Adams, B., and W.W. Adams III, 1996, "The Role of Xanthophyll Cycle Carotenoids in the Protection of Photosynthesis," *Trends in Plant Science* , vol. 1, pp. 21-26.

Filella, I., T. Amaro, J.L. Araus, and J. Peñuelas, 1996, "Relationship between photosynthetic radiation-use efficiency of barley canopies and the photochemical reflectance index (PRI)," *Physiol. Plant*, vol. 96, pp 211-216.

Gamon, J.A., R.O. Green, D.A. Roberts, and L. Serrano, 1995, "Deriving Photosynthetic Function from Calibrated Imaging Spectrometry," pp. 55-60 in: Guyot, G. (ed.) *Proceedings of the International Colloquium. Photosynthesis and Remote Sensing*. 28-30 August, 1995. Montpellier, France.

Gamon, J.A., L. Serrano, and J.S. Surfus , 1997, "The Photochemical Reflectance Index: an Optical Indicator of Photosynthetic Radiation Use Efficiency across Species, Functional Types, and Nutrient Levels." *Oecologia*, vol. 112 (2), pp. 492-501.

Gamon, J.A., C.B. Field, M.L. Goulden, K.L. Griffin, A.E. Hartley, G. Joel, J. Peñuelas, and R. Valentini, 1995, "Relationships between NDVI, Canopy Structure, and Photosynthesis in Three Californian Vegetation Types," *Ecological Applications* 5(1), pp. 28-41.

Gamon, J.A., J. Peñuelas, and C.B. Field, 1992, "A narrow-waveband spectral index that tracks diurnal changes in photosynthetic efficiency," *Remote Sensing of Environment*, vol. 41, pp 35-44.

Goetz, A.F.H., K.B. Heidebrecht, B. Kindel, and J.W. Boardman, 1998, "Using Ground Spectral Irradiance for Model Correction of AVIRIS Data," *Summaries of the Seventh Annual JPL Earth Science Workshop*, January 12-16, 1998 (this volume).

Green, R.O., J.E. Conel, D.A. Roberts, 1993, "Estimation of Aerosol Optical Depth and Additional Atmospheric Parameters for the Calculation of Apparent Reflectance from Radiance Measured by the Airborne Visible/Infrared Imaging Spectrometer," In: *Summaries of the Fourth Annual JPL Airborne Geoscience Workshop*, Oct. 25-29, 1993, Washington, DC, vol. 1, pp. 73-76.

Hall, F.G., J.R. Townshend, and E.T. Engman, 1995, "Status of Remote Sensing Algorithms for Estimation of Land Surface State Parameters," *Remote Sensing of Environmentt*, vol. 51, pp. 138-156.

Hatfield, J.L., G. Asrar, and E.T. Kanemasu, 1984, "Intercepted Photosynthetically Active Radiation Estimated by Spectral Reflectance," *Remote Sensing of Environment*. 14:65-75.

Koide, R.T., R.H. Robichaux, S.R. Morse, and C.M. Smith, 1989, "Plant Water Status, Hydraulic Resistance, and Capacitance," pp. 161-183, in: Pearcy R.W., J. Ehleringer, H.A. Mooney, and P.W. Rundel (eds), *Plant Physiological Ecology: Field Methods and Instrumentation*, Chapman and Hall, London.

Kumar. M, and J.L. Monteith, 1981, "Remote Sensing of Crop Growth," In: Smith, H (Ed) *Plants and the Daylight Spectrum*. Academic Press. London, England, pp. 133-144.

Mooney, H.A., A.T. Harrison, and P.A. Morrow, 1975, "Environmental limitations of photosynthesis on a California evergreen shrub," *Oecologia* vol. 19, pp 293-301.

Nemani. R., and S. Running (1997) "Land cover characterization using multitemporal red, near-IR, and thermal-IR data from NOAA/AVHRR," *Ecological Applications*, vol 7, pp. 79-90.

Peñuelas, J., I. Filella, and J.A. Gamon, 1995, "Assessment of Photosynthetic Radiation-Use Efficiency with Spectral Reflectance," *New Phytol*. vol. 131, pp. 291-296.

Peñuelas, J., I. Filella, C. Biel , L. Serrano, R. Savé, 1993, "The Reflectance at the 950-970 nm Region as an Indicator of Plant Water Status," *Int. J. Remote Sensing*, vol. 14, no. 10, pp. 1887-1905.

Peñuelas, J., J. Llusia, J. Piñol, and I. Filella, 1997, "Photochemical Reflectance Index and Leaf Photosynthetic Radiation-Use-Efficiency Assessment in Mediterranean Trees," *Int. J. Remote Sensing*, vol. 18, pp. 2863-2868.

Peñuelas, J., J. Piñol, R. Ogaya, and I. Filella, 1997, "Estimation of Plant Water Concentration by Reflectance Water Index WI (R900/R970)," *Int. J. Remote Sensing* , vol. 18, no. 13, pp. 2869-2875.

Prince, S.D., and S.N. Goward, 1995, "Global Primary Production: a Remote Sensing Approach," *Journal of Biogeography*, vol. 22, pp. 815-835.

Roberts, D.A., R.O. Green, and J.B. Adams, 1997, "Temporal and Spatial Patterns in Vegetation and Atmospheric Properties from AVIRIS," *Remote Sens. Environ.*, vol. 62, pp. 223-240.

Sanderson, E.W., M.H. Zhang, and S.L. Ustin, in press, "Geostatistical Scaling of Canopy Water Content in a California Salt Marsh: Bridging the Gap Between Ecology and Remote Sensing." *Landscape Ecology*.

Sellers, P.J., 1985, "Canopy Reflectance, Photosynthesis, and Transpiration," *International Journal of Remote Sensing*. 6:1335-1372.

Sellers, P.J., B.W. Meeson, F.G. Hall, G. Asrar, R.E. Murphy, R.A. Schiffer, F.P. Bretherton, R.E. Dickinson, R.G. Ellingson, C.B. Field, K.F. Huemmrich, C.O. Justice, J.M. Melack, N.T. Roulet, D.S. Schimel, and P.D. Try, 1995, "Remote Sensing of the Land Surface for Studies of Global Change: Models - Algorithms - Experiments," *Remote Sensing of Environment*, vol. 51, pp. 3-26.

Sellers, P.J., L. Bounoua, G.J. Collatz, D.A. Randall, D.A. Dazlich, S.O. Los, J.A. Berry, I. Fung, C.J. Tucker, C.B. Field, and T.G. Jensen, 1996, "Comparison of Radiative and Physiological Effects of Doubled Atmospheric CO_2 on Climate." *Science*, vol. 271, pp. 1402-1406.

Tenhunen, J.D., A. Sala Sera, P.C. Harley, R.L. Dougherty, and J.F. Reynolds, 1990, "Factors Influencing Carbon Fixation and Water Use by Mediterranean Sclerophyll Shrubs during Summer Drought." *Oecologia* 82:381-393.

Tenhunen, J.D., O.L. Lange, J. Geberl, W. Beyschlag, and J.A. Weber, 1984, "Changes in Photosynthetic Capacity, Carboxylation Efficiency, and CO_2 Compensation Point Associated with Midday Stomatal Closure and Midday Depression of Net CO_2 Exchange of Leaves of *Quercus suber*," *Planta* 162:193-203.

Tenhunen, J.D., O.L. Lange, P.C. Harley, W. Beyschlag, and A. Meyer, 1985, "Limitations Due to Water Stress on Leaf Net Photosynthesis of *Quercus coccifera* in the Portuguese Evergreen Scrub," *Oecologia* 67:23-30.

Ustin S.L., D.A. Roberts, J. Pinzón, S. Jacquemoud, M. Gardner, G. Scheer, C.M. Casteñada, A. Palacios-Orueta, in press, "Estimating Canopy Water Content of Chaparral Shrubs using Optical Methods," *Remote Sensing of Environment*.

Zhang, M, S.L. Ustin, E. Rejmankova, and E.W. Sanderson, 1997, "Remote Sensing of Salt Marshes: Potential for Monitoring." *Ecological Applications*. 7(3):1039-1053.