WATER EXPRESSIONS FROM HYPERSPECTRAL REFLECTANCE: IMPLICATIONS FOR ECOSYSTEM FLUX MODELING

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1. INTRODUCTION

Remote sensing is often used to provide spatially explicit inputs ecosystem primary production models (Field et al. 1995). Most of these efforts utilize broad-band satellite sensors. Hyperspectral sensors can potentially improve ecosystem process models by providing alternate model inputs based on fundamental biophysical and biochemical properties linked to physiological function (Gamon and Qiu 1999). Water and pigments provide examples of physiologically relevant compounds present in vegetation that are detectable based on absorption features present in hyperspectral data.

Several different expressions of canopy water content have been derived from AVIRIS data. These include Beer's Law fits of absorption coefficient spectra (Green et al. 1993, Roberts et al. 1997 and 1998, Ustin et al. 1998), hierarchical foreground-background analysis (Ustin et al. 1998, Pinzon et al.1998), continuum removal (Zhang et al. 1996, Sanderson et al. 1998), and the water band index (WBI) based on reflectance at 900 and 970 nm (Peñuelas et al. 1993, 1994, and 1997, Gamon et al. 1998, Gamon and Qiu 1999). Ecophysiological studies using field spectrometry have shown that the water band index can provide useful measures of changing plant water content (Peñuelas et al. 1993, 1994, and 1997). In southern Californian chaparral vegetation, this index can readily detect seasonally changing water content, which may provide a useful way to estimate changing vegetation-atmosphere fluxes of water and carbon dioxide (Gamon and Qiu 1999). However, the quantitative relationships between reflectance-derived expressions of water, actual canopy water content, and changing physiological performance, remain largely unexplored for several reasons. Accurate expressions of water absorption in hyperspectral imagery depend upon proper atmospheric correction, which is not always possible. Furthermore, AVIRIS samples at a grain size (IFOV roughly 18 m diameter) that is at least one order of magnitude larger than what can readily be sampled on the ground using traditional physiological sampling methods (<1 cm^2 to 1 m^2), and this difference in sampling scale is one reason that AVIRIS-derived water expressions of water have not been more fully tested. Additionally, problems of spatial and temporal mis-matches between AVIRIS and ground sampling further compound the difficulties of validating expressions of water content in AVIRIS imagery (Sanderson et al. 1998).

As part of a larger study of ecosystem function in Southern California chaparral, we have been investigating expressions of water and pigment content derived from hyperspectral reflectance as potential indicators of seasonally and diurnally changing carbon and water vapor fluxes. Here we present initial results from field sampling and from the fall 1998 low altitude deployment, with a primary focus on the practical significance of the 970 nm water absorption band. One goal of this study was to confirm the utility of the water band index as a measure of canopy water content. A second goal was to compare the water band index to other expressions of water content derived from AVIRIS imagery. A third goal was to examine the effect of spatial scale (pixel size or grain size) on the measurement of physiological variables, with a particular focus on water content. Meeting these goals is a fundamental prerequisite to using water signals present in hyperspectral imagery in improved models of vegetation-atmosphere fluxes.

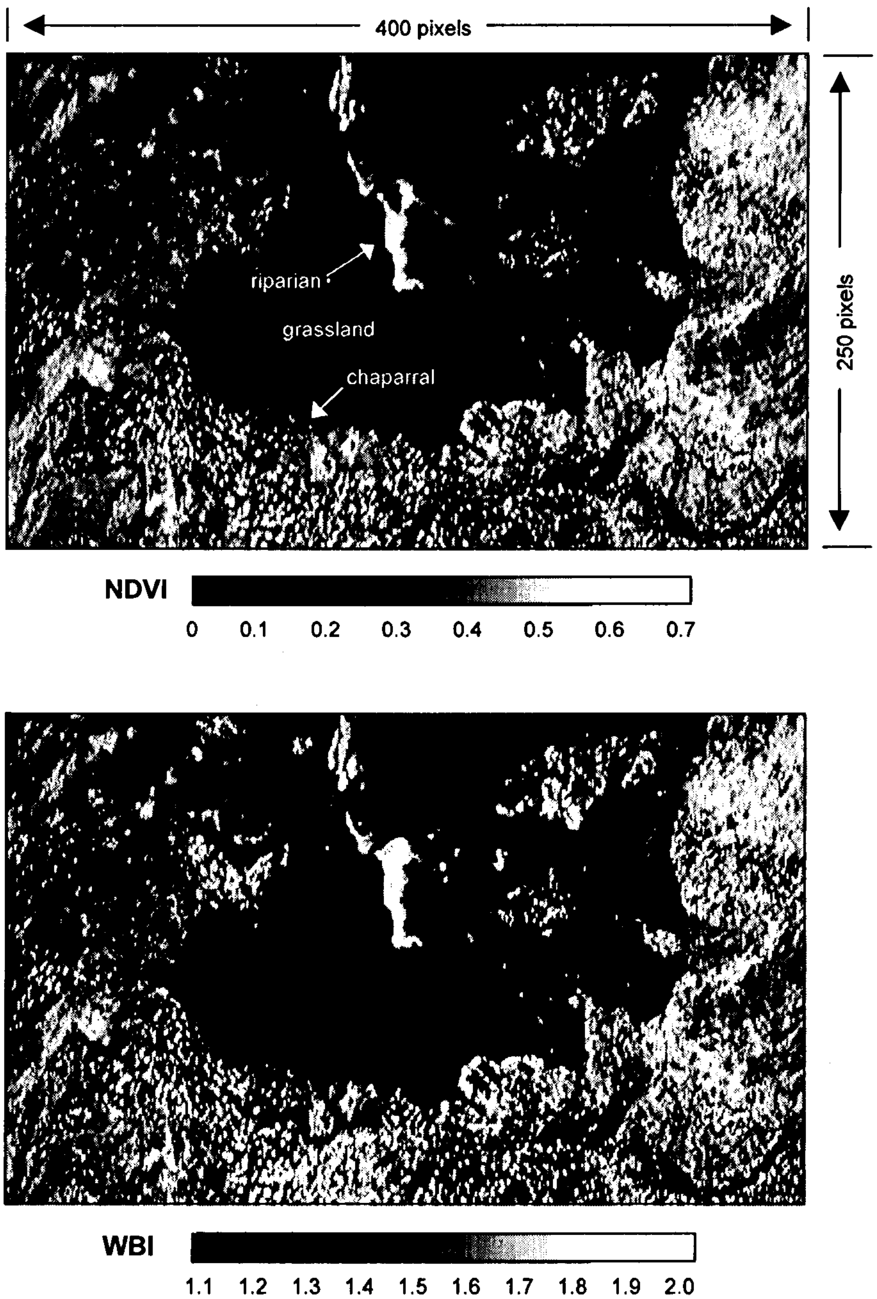

Figure 1. Low altitude AVIRIS radiance scene dated 27 October 1998 from the Rancho Sierra Vista site in the Santa Monica Mountains, CA (34° 8' 32" N, 118° 57' 19"). Note similar landscape patterns for NDVI (top panel) and WBI (bottom panel), suggesting that most of the water detectable in this image is present in green leaves. Also indicated (top panel) are riparian, grassland, and chaparral areas sampled in this study (only grassland and chaparral results are presented). In this low-altitude image (pixel size approx. 4 x 4 m) bright spots indicate individual canopies or small patches of relatively uniform shrub or tree cover, generally not resolvable in high altitude scenes.

2. MATERIALS AND METHODS

This study was conducted in the Santa Monica Mountains, California, during 18-21 May (spring) and 28 October (fall), 1998, using a combination of field sampling and AVIRIS data. The intention was to obtain simultaneous field and aircraft data in two seasons of contrasting water availability and physiological activity. The study area was a grassland region ("Rancho Sierra Vista" with center coordinates of 34° 8' 32" N, 118° 57' 19" W), having adjacent riparian and chaparral vegetation (figure 1).

Field sampling was conducted in both spring and fall, but simultaneous AVIRIS data were available only in the fall in the form of a low-altitude flight obtained on 28 October, 1998. All analysis of this scene was conducted on radiance data, uncorrected for atmospheric effects or geometric distortion. High altitude flights, while obtained in both spring and fall, had been rescheduled and thus had not been obtained under comparable conditions as the field sampling, precluding any direct comparison to field data. However, some limited analysis of high altitude AVIRIS data is presented below from a previous AVIRIS flight (961017 run 4, scene 6). This scene had been processed to reflectance using the procedure of Green et al (1991 and 1993).

Field sampling was conducted along permanent transects in each vegetation type with a field spectrometer (UniSpec, PP Systems, Haverhill, MA) fitted with a straight fiber foreoptic. The end of this fiber optic, which was positioned 3 meters above the ground, yielded a field-of view of approximately 20 degrees, resulting in a "pixel size" of approximately 1 meter on the ground. By continuously scanning while walking along pre-marked transects in each vegetation type, we were able to obtain spatially contiguous ground spectra at a 1-meter grain size, allowing us to simulate larger pixel sizes corresponding to the AVIRIS imagery. In the spring, immediately following optical sampling, a number of grassland locations were harvested for determination of fresh and dry above-ground biomass and species composition.

Two expressions of water content were used in this study: 1) the "Water Band Index" (WBI), which is the ratio of reflectance (or radiance) at 900 and 970 nm (Peñuelas et al. 1997, Gamon and Qiu 1999), and 2) "equivalent water thickness," which is obtained by fitting a water absorption coefficient spectrum to reflectance using Beer's Law (Green et al. 1993, Roberts et al. 1997 and 1998). To compare the WBI against actual canopy water content, annual grassland vegetation was harvested in spring, 1998, immediately following field reflectance measurements. The harvested canopy material was placed in sealed plastic bags in ice chests for transport to a lab, where water mass was calculated as the difference between fresh and oven-dried biomass.

3. RESULTS AND DISCUSSION

3.1 The Significance of the 970 nm Water Band

Figure 1 presents a radiance scene from the low-altitude AVIRIS deployment that includes the riparian, grassland, and chaparral vegetation types sampled in the field (only grassland and chaparral data are presented here). Note the similar landscape patterns for NDVI (top panel) and WBI (bottom panel), suggesting that most of the water detectable in this image is present in green leaves. In this low-altitude image (pixel diameter approximately 4 m) bright spots indicate individual canopies or small patches of relatively uniform shrub or tree cover, generally not resolvable in high altitude scenes (not shown).

Field sampling revealed a strong correlation between the water band index (WBI) and actual canopy water content (figure 2), at least for the one date and vegetation type sampled. More work is needed to test this relationship under a wider range of seasons and vegetation types. However, this preliminary result supports the hypothesis that WBI is largely driven by variation in actual canopy water content, which impacts both canopy structure and physiology.

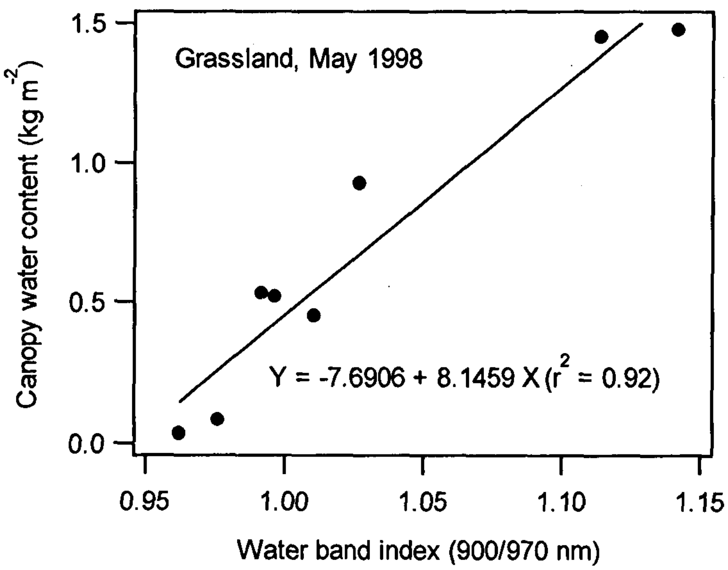

Figure 2. Canopy water content from harvests plotted against water band index (WBI) for grassland sampled from the ground in spring, 1998.

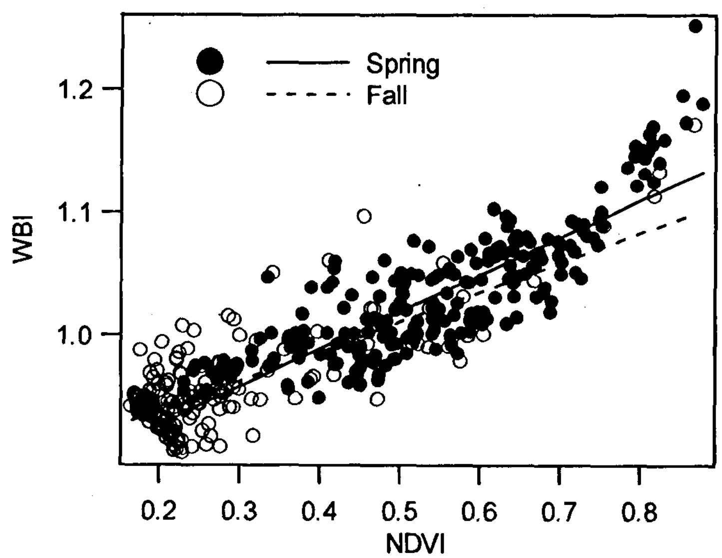

Figure 3. Plot of water band index (WBI) vs. normalized difference vegetation index (NDVI) for grassland and chaparral vegetation sampled in spring and fall, 1998.

Field sampling also revealed a strong association between WBI and the normalized difference vegetation index (NDVI - Figure 3). This indicates that most of the variability in WBI is driven by canopy structural properties associated with the amount of live, moist canopy materials. However, a careful comparison of spring and fall WBI-NDVI regressions revealed a subtle decline in slope with the onset of drought conditions (solid vs. dashed lines, Figure 3). Qualitatively similar seasonal changes in this relationship for these vegetation types has been reported before, both in ground sampling (Gamon et al. 1998) and AVIRIS data (Gamon and Qiu 1999). This subtle seasonal shift in the WBI-NDVI relationship suggests that some portion of changing water content detectable by WBI is associated with changing leaf-level water concentration rather than with canopy structure *per se*. Alternatively, this shift could reflect a decline in the proportion of total canopy water present in green leaves (e.g., a greater proportion detectable in stems as leaf orientation or leaf area index changes with drought). Further experimental work is needed to determine the underlying cause of this seasonal shift. It may be possible to use this feature to separate physiologically significant changes in water status (the slope change) from the dominating effect of canopy structure on WBI. Because seasonally changing canopy structure and leaf water status are associated with strong declines in photosynthetic activity in these vegetation types, the water band index may provide a means of detecting seasonal changes in carbon dioxide and water vapor fluxes in this landscape. However, more work is needed to develop quantitative relationships between hyperspectral expressions of changing water status and actual physiological function.

3.2 Comparison of Different Expressions of Water Content

Analysis of AVIRIS imagery demonstrated that the water band index (WBI) is also strongly correlated to "equivalent water thickness" estimated using a Beer's Law fit (Figure 4). The larger scatter at lower values reflects the greater uncertainty in water estimates when there is little canopy water present, and the diminished water absorption feature is increasingly influenced by noise. More work is needed to compare the several algorithms used for expressing liquid water, and to reduce the uncertainty in water estimates at low water content values. However, this limited analysis suggests that "equivalent water thickness" - another published expression of liquid water (e.g., Green et al. 1993, Roberts et al. 1997, Ustin et al. 1998) - is functionally equivalent to the water band index.

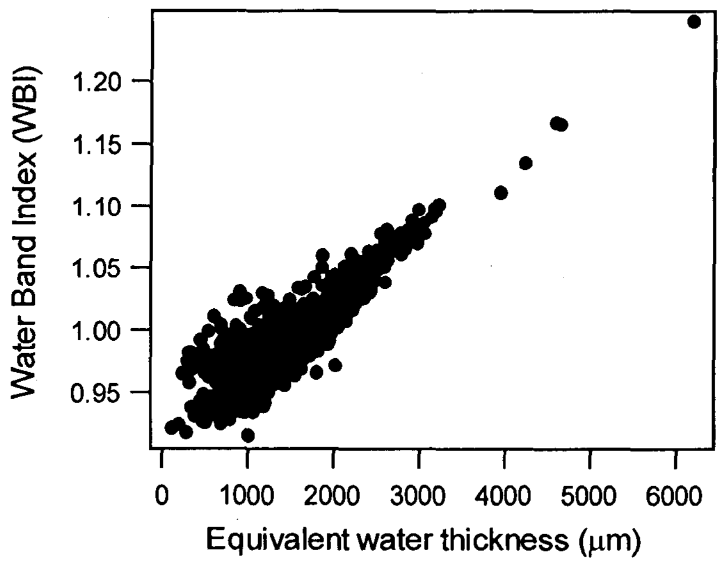

Figure 4. Correlation between the water band index (WBI) and equivalent water thickness, derived from AVIRIS (flight 961017, run 4, scene 6) processed to surface reflectance.

3.3 Effect of Spatial Scale

Ground sampling of the water band index (WBI) at a 1-meter grain size revealed fine-scale patterns associated with individual plant canopies and fine-scale patches of uniform vegetation. These fine-scale patterns varied dramatically with vegetation type and season (Figure 5). For example, chaparral contains evergreen species that retain live leaves into the fall, interspersed by deciduous and annual species that shed leaves with the onset of summer drought. This resulted in a transition from many individual WBI

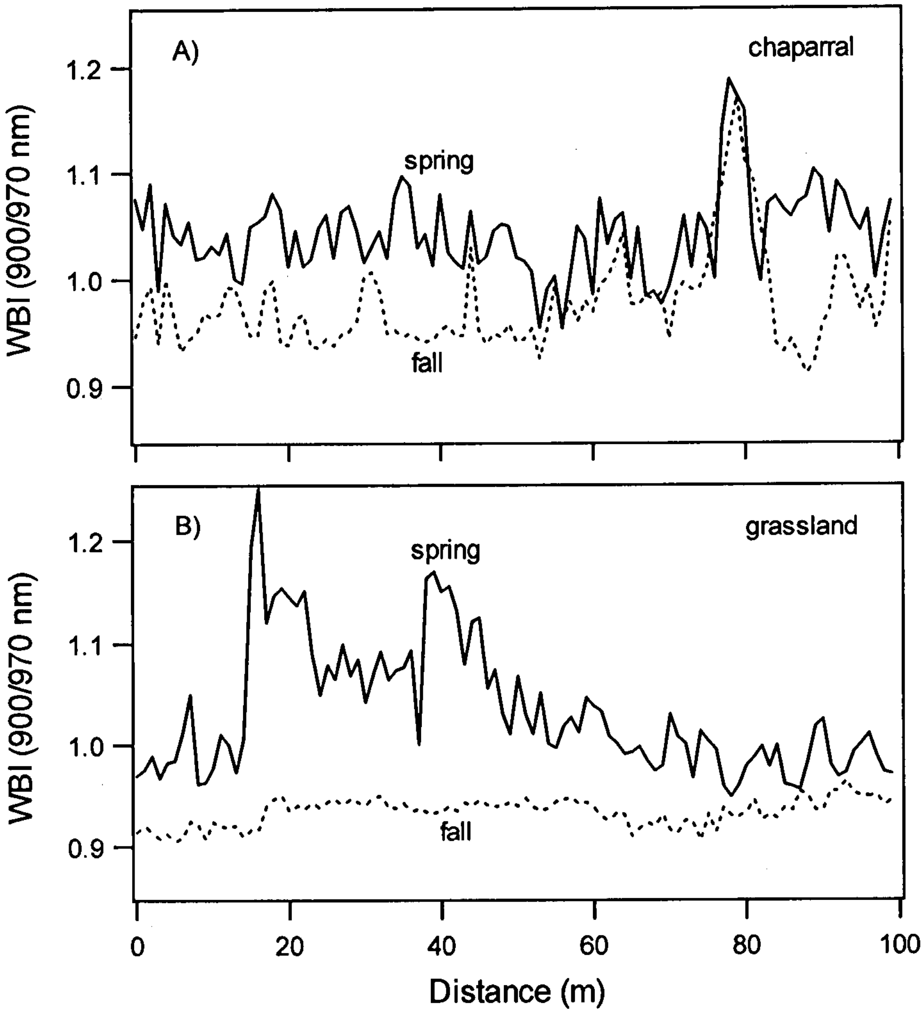

Figure 5. Water band index (WBI) transects, sampled from the ground in spring and fall, 1998, for the chaparral (panel A) and grassland (panel B) regions indicated in figure 1. Fine-scale peaks in WBI represent individual shrub canopies or patches of annual vegetation having high water content. The large spike near 80 m in the chaparral (panel A) is due to a particularly large individual shrub (*Malosma laurina*). The broad peaks near 20 and 40 m in the grassland (panel B) are due to patches of productive annual vegetation located near the bottom of a swale.

peaks in spring to fewer, more widely spaced peaks in fall (Figure 5A). Similarly, the grassland displayed many WBI peaks due to small patches of photosynthetically active plants in the spring. However, all of these grassland patches had lost canopy moisture by fall with the onset of senescence (Figure 5B). Also visible in both chaparral and grassland transects are larger scale productivity gradient associated with topographic features. For example, in the grassland, the high WBI values between 15 and 50 meters corresponded to moist, productive vegetation growing along the bottom of a swale. The low WBI values from 0 to 60 meters in the chaparral corresponded to a ridge crest, whereas the high peak near 80 meters represented a particularly large evergreen shrub (*Malosma laurina*) further down the slope.

To further examine the effect of sampling scale on WBI, we compared fine-grain ground sampling (1-meter pixel diameter) to coarser grained AVIRIS data (4-meter pixel diameter- Figure 6). Additionally, for both the 1-meter and the 4-meter data sets, we simulated the effect of coarser-scale sampling. In this simulation, 1-meter field data was degraded to 4 meters to approximate the scale of low-altitude AVIRIS data (dashed line, figure 6A). The 4-meter (low altitude) AVIRIS data was degraded to 20 meters to approximate the scale of high-altitude AVIRIS data (dashed line, Figure 6B), which was not available for this date. The simulated 4-meter data derived from field sampling (dashed line, Figure 6A) showed a similar trend as the measured 4-meter data derived from AVIRIS (solid line, Figure 6B). This agreement suggested that the simulation provided a reasonable estimate of coarser-scale data (missing in the case of the high-altitude flight). The difference in Y-axis scales between panels 6A and B were due to the fact that panel A was calculated from reflectance, whereas panel B was calculated from radiance. We hope to repeat this analysis if a valid surface reflectance can be retrieved for this image.

Several conclusions can be drawn from this analysis of scale. One conclusion is that this chaparral landscape contains a fine-scale variability in WBI that is primarily associated with patterns of individual shrub canopies. This fine scale variability is largely missing from the low altitude (4 meter) AVIRIS data, and entirely missing from the simulated high altitude (20 meter) data. Clearly, high altitude AVIRIS imagery fails to capture physiologically significant patterns of water content associated with individual canopies in this landscape. The finer scale, low-altitude data succeeded in resolving the WBI of large shrub canopies (e.g., the peak in WBI near 80 meters due to a single, large shrub). However, much of the finer scale variability associated with the smaller individuals is lost even in the 4-meter data. However, both the 4- meter and 20-meter scale AVIRIS data readily reveal the larger landscape gradients in productivity associated with topography.

The importance of spatial scale varies with the process under examination, and to a large extent depends upon whether that process scales linearly or non-linearly with size (Ehleringer and Field 1993). Although not fully examined in this study, the effect of spatial scale on the interpretation of WBI could vary depending upon the patchiness of the landscape and upon whether the surface is wet or dry. In this study, soil and plant surfaces were visibly dry, so we did not evaluate the potentially confounding influence of varying surface moisture on physiological interpretations of WBI. In other, ongoing studies of this landscape (not shown) we have been evaluating the effect of spatial scale and patchiness on physiological interpretations of pigment content and activity. For example, the photochemical reflectance index (PRI) is an index of xanthophyll pigment activity and photosynthetic performance at the leaf and canopy scales. Our studies to date suggest that useful expressions of xanthophyll pigments and photosynthetic activity can be derived from hyperspectral data, particularly if individual plant canopies can be resolved (e.g., Gamon and Qiu 1999). However, the interpretation of PRI remains unclear in high-altitude AVIRIS imagery where vegetation signals are typically confounded by contributions from other scene components, including soil (Gamon et al. 1995). Recent results (not shown) indicate that background color (e.g., soil color or degree of shade) can have a strong influence on how spatial scale impacts the meaning of this index. Consequently, sampling scale may strongly influence the ability to determine physiological function from hyperspectral signals. Unlike high-altitude data, which inevitably contains mixed pixels, low altitude data can resolve some of the larger canopies and physiologically homogenous patches in this landscape. Consequently, we conclude that low altitude AVIRIS data, along with concurrent ground sampling, represent significant improvements over high-altitude AVIRIS data for physiological studies. However, for purposes of classifying broad vegetation types or defining coarse landscape gradients in productivity, high-altitude AVIRIS data appear to be sufficient.

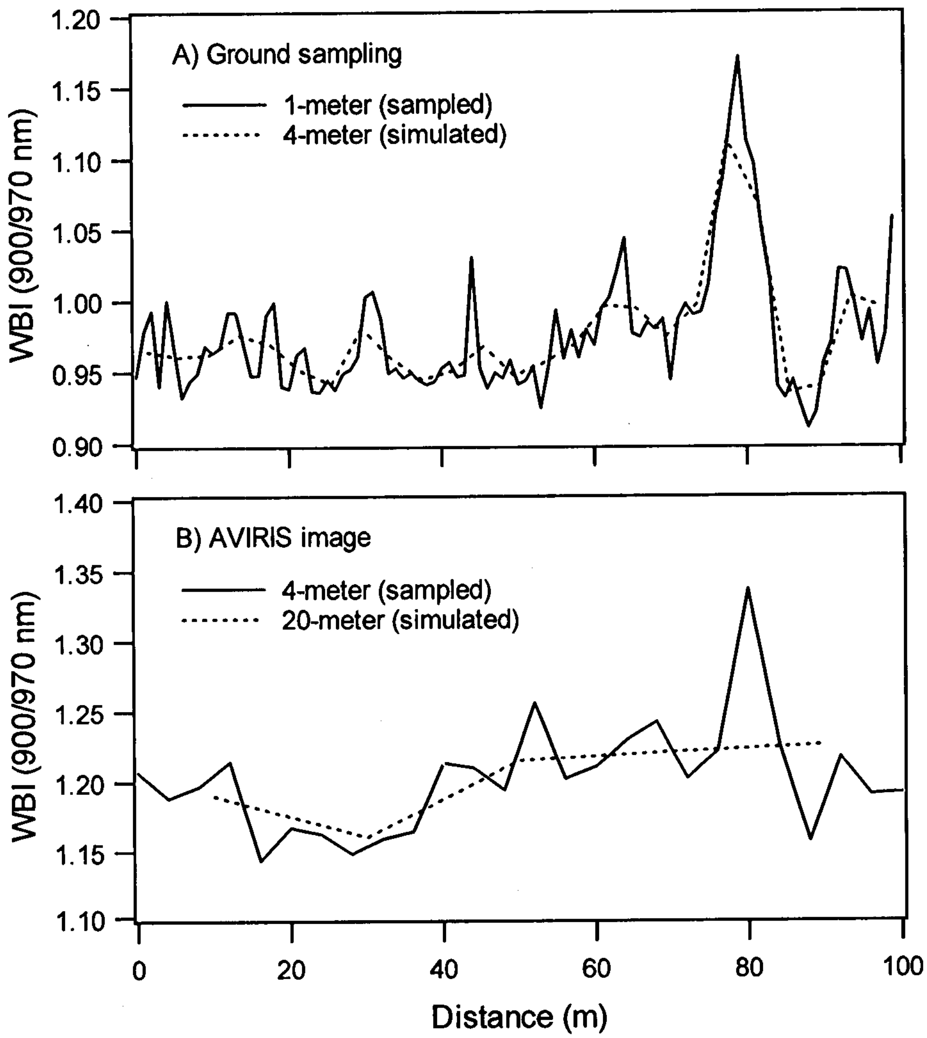

Figure 6. Water band index (WBI) transects sampled (solid lines) and simulated (dashed lines) both from the ground (panel A) and from AVIRIS low-altitude data (panel B) for the same chaparral region indicated in figure 1 (sampled 28 October, 1998).

4. FINAL COMMENTS

Considerable challenges remain in validating expressions of water or pigment content or activity from AVIRIS data, partly because of the difference in scales between AVIRIS and ground sampling. Further low-altitude deployments, combined with concurrent ground sampling, could be very useful in resolving lingering questions. However, to properly validate physiological signals, it is essential to provide close coordination in both time and space between AVIRIS flights and field sampling, as physiological state varies dramatically over small space (meters) and time (hours) scales. This situation is fundamentally different from other signals (e.g., geological signals or canopy structural signals) that change more slowly in time. Consequently, further deployments of hyperspectral imaging instruments must emphasize a close degree of coordination between ground physiological sampling and flight teams if these issues are to be fully resolved. Additionally, because accurate atmospheric correction for water vapor is critical for proper retrieval of surface reflectance, development of routine, reliable, and widely accessible procedure for atmospheric correction would greatly facilitate quantitative interpretation of water expressions in AVIRIS imagery. Because of the strong links between vegetation water status and physiological performance, reliable, quantitative expressions of water status from hyperspectral imagery would greatly assist efforts to model vegetation-atmosphere fluxes over large regions.

5. ACKNOWLEDGMENTS

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