Sierra Nevada Forest Stress Determination From AVIRIS Data

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ABSTRACT
AVIRIS hyper-spectral remotely sensed data collected in the fall of 1989 over control and stressed Ponderosa pine (*Pinus Ponderosa*) stands in the lower elevation, western-most reaches of the Tahoe National Forest, California were examined. The forests of the Sierra Nevada had been subjected to three years of drought and an associated Western Pine Beetle (*Dendroctonus brevicomis*) presence. Two drought/beetle stress sites and two healthy/control sites were selected for canopy spectral analysis. AVIRIS data sets were reduced to non-coincident, low-noise bands and three spectral analysis procedures were implemented to determine healthy and stressed vegetation components. Full wavelength spectral analysis of the sites, first derivative approximations for red-edge shifts, and a Moisture Stress Index (MSI) calculation were performed.

Our initial findings indicate that spectral separation is possible when comparing full spectra plots, with spectral discrimination highest at 820-860nm and 1003-1023nm; no significant red-edge shifts could be determined; and, the MSI indicated a slight difference in the stress and control sites. Other conditions related to the analysis of the sites will be discussed, including the difficulties associated with selection of homogeneous control and stress plots.

I. INTRODUCTION

As of 1989, three consecutive drought years had stressed the forest stands in the Sierra Nevada of California; a drought unprecedented in the last 500 years. The drought has increased the forests susceptibility to insect and disease attack. The combination of moisture deprivation and an invasion of the Western Pine Beetle and Fir Engraver Beetle (*Scolytus ventralis*) have left the forest stands in serious danger of propagating extensive wildfires. Because these stresses affect the forest biophysical parameters, primarily leaf moisture content and chlorophyll alterations, NASA and the U.S. Forest Service are experimenting with utilizing the narrow-band, hyper-spectral AVIRIS scanner for determination of stressed canopy conditions. We have initially employed three methods to determine spectral separability of stressed and healthy canopies: full spectrum comparative analysis, first derivative analysis for red edge spectral position changes, and the calculation of a Moisture Stress Index (Miller, et al., 1990; Miller, et al., 1990; Rock, et al., 1986).

This paper will address preliminary results of our analysis of data collected with the NASA-JPL Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) over a mixed forest canopy site near Nevada City, California within the Tahoe National Forest of the Sierra Nevada range. The AVIRIS data was collected on-board the NASA-Ames ER-2 high altitude aircraft on 4 October 1989 (Flight 90-004) from an altitude of 65,000 feet (19.8 km). Data collection occurred at 12:28 PM local time. An RC-10 camera with 9x9 inch format CIR film collected simultaneous data from the same platform.

A. Study Site Description
Four study sites were located in the AVIRIS data for analysis. All four sites are east of Nevada City, California at the western-most edge of the Tahoe National Forest. Elevation in the vicinity of the sites ranges from 3000-5000 feet. In this elevation range, a transitional forest exists. Lower elevations are dominated by open Manzanita (*Arctostaphylos*) brush fields with scattered Digger Pine (*Pinus Sabiniana*), Oaks, and some Ponderosa pine. Black oak (*Quercus kelloggii*) and Canyon Live Oak (*Q. chrysolepis*) occur in the mid-lower elevation ranges, usually in the river canyons and on moist slopes. As elevation increases, a change from broadleaf to conifer occurs. The mid-elevation ranges of the AVIRIS scene area include scattered Sugar pine (*P. lambertiana*) and Incense Cedar (*Libocedrus decurrens*). Ponderosa pine is found in small discontinuous stands in the remainder of the area, with Red Fir (*Abies magnifica*) and White Fir (*A. concolor)* rarely occurring in any definitive stands at this elevation.

Because of the discontinuous nature of the Ponderosa pine stands in the AVIRIS scene area, it was difficult to select control and stressed sites with similar size and age classes, crown closures and elevation characteristics. In order to facilitate spectral comparisons, we attempted to select sites with full crown closure. This reduced the likelihood of spectral contamination from understory components or bare soils/rocks. Four total sites, two control and two stressed, were selected upon examination of the available aerial photography. Control site 1, at 3800' elevation, contained 100% crown closure of Ponderosa pine with a dominance of mature timber (even age stand). Control site 2, at 4400-4600' elevation, was located on a North aspect with 80% crown closure and a mix of Ponderosa pine classes from small saw to mature saw timber. Stress site 1, located at 3800' elevation, contained 100% crown closure and evident crown needle damage on approximately 20% of the stand. Stress site 2, located at 4700-4800' elevation had an 80% crown closure of mixed size class Ponderosa pine. Damaged or stresses crowns were estimated at 35-40% of the stand. Both combinations of sites are in close proximity to each other and were selected from both the north and south sides of the South Yuba River, which runs east to west through the area.

II. DATA PREPARATION AND ANALYSIS
Two adjacent AVIRIS scenes, collected minutes apart were analyzed. Site 1 control and stress were located on the western-most scene of the two, and site 2 on the eastern. The eastern scene represented an area of slightly higher elevation. Prior to analysis, the AVIRIS data was examined and band overlap regions were eliminated, as were bands with low signal/noise ratios. From the original 224 bands, 4 overlap bands at the A/B spectrometer cross-over were eliminated; 5 at the B/C spectrometer cross-over; and 5 at the C/D spectrometer cross-over. This resulted in 210 contiguous bands (396.9-2455 nm). Because of low signal/noise ratios and general low contrast, the first 10 bands (396.9-485.7 nm) of the A spectrometer and the last 12 bands of the D spectrometer (2346-2455 nm) were not utilized in the analysis. The first 10 bands of A, in the blue EMS region had high atmospheric attenuation and low signal/noise ratios. The last 12 bands of the D spectrometers contained low signal/noise ratios as well as bands with no evident spectral data. The final data set therefore consisted of 188 bands with a spectral range of 495.6-2336 nanometers. These 188 bands were utilized for the full spectrum comparisons and to derive spectral statistics for analysis. Some of the bands in this spectral range had reduced radiance values due to H_2O, CO_2, and O_2 absorption frequencies. These bands were retained in the data set for spectral continuity. Those specific absorption features can be seen as local minimum radiance values in the plotted spectra; the strongest absorptions occurring at 940 and 1140 nm (H_2O).

Sub-windows surrounding each of the four sites were delineated. In comparing the two sets of control/stress sites, areas of similar pixel dimensions were selected to derive the statistics. This procedure avoided any spectral differences due to a lack of statistically valid sample sizes. Control site 1 was composed of 375 pixels; Stress site 1, 275 pixels; Control site 2, 156 pixels; and Stress site 2, 154 pixels. Statistics for the sites were not merged due to their different characteristics (elevation, aspect position, and size classes). The mean radiance for each site (and each band) was calculated and used to derive the spectral plots. The mean radiance of the sub-window was determined by moving an average filter window of the same dimensions as the site, by an x-y distance equal to the dimension also. This creates a single pixel mean window value data set composed of 188 bands. Since the original AVIRIS radiometric data set was scaled by a factor of 200 to retain precision as a 16-bit integer, the mean spectral values were divided by 200 to derive the actual radiance value per band for the mean window.

Three methods were employed on the mean site spectral data to determine the separability of control and stressed Ponderosa pine sites. Initially, full spectral plots of the mean radiance counts per wave-band were derived. An attempt was also made to identify changes in the position of the red edge reflectance curve by deriving a first derivative calculation of the spectral data between 604 nm and 800 nm. Finally, we calculated the Moisture Stress Index (MSI) from two wave-bands to determine variations in moisture stress on the canopy reflectance.

A. Full Spectral Comparative Analysis

For each pair of sites (Site 1 control/stress; Site 2 control/stress), mean radiance ($\mu W\ cm^{-2} nm^{-1} sr^{-1}$) values were plotted for the wavelength region 496 nm to 2336 nm (Figure 1).

1. Site 1

As can be seen in Figure 1 (Site 1), the spectra for the stressed site is higher than the control from the blue-green region through the red trough (local minimum). In the transition from the red to the near-IR, the stressed and the control spectra track similarly with little noted shift in the red edge or the inflection point for either. As can be expected, the stressed radiance tracks lower than the control throughout the IR plateau and the remainder of the IR to the H_2O and CO_2 absorption frequency in the vicinity of 1370 nm. Beyond this absorption area, the stressed and control Ponderosa pine spectra display unique peaks at 1440 nm.

2. Site 2

The radiance plots for site 2 are shown in Figure 2. The stress site spectra tracks similar to the control site from the blue-green through the red trough. Similar to site 1, both spectra are virtually inseparable along the red/IR transition. At the IR plateau, the stressed spectra remains higher than the control site. Unlike site 1, there is no unique spectral spike at 1440 nm in either the control or stressed site 2.

B. "Red-Edge" Detection

The red-edge spectral position is a vegetation parameter related primarily to the rise and fall of leaf (needle) chlorophyll content (Miller, et al., 1990). Vegetation spectra exhibit a consistent shape in the red-edge region characterized by a broad, flat minimum at ~670 nm (see Figures 1 and 2), with an increase starting at ~685 nm, reaching to an asymptotic IR plateau beyond 780 nm (Miller, et al., 1990). It has been noted that changes in the plant chlorophyll content due to stress alter the red-edge spectral position. Given less apparent chlorophyll in the stressed needle, the slope of the spectral curve changes in the 680-720 nm region. As chlorophyll decreases, the radiance increases in the red trough (chlorophyll well), and the spectral position of the red-edge inflection point shifts towards shorter wavelengths. In the near-IR plateau region, the spectral position of stressed Ponderosa pine should be lower than a chlorophyll-rich, healthy Ponderosa pine stand. Conversely, the more chlorophyll concentration, the stronger the shift of the inflection point to longer wavelengths, with an accompanying increased IR plateau (Ustin, et al., 1990).

We employed a first derivative approximation of the spectral profile to determine the presence of the red-edge shift. The approximation of the first derivative was calculated for the 604nm-800nm spectral region, and is represented by the equation:

$$R_N - R_{N-1} / W_N - W_{N-1}$$

where R is the radiance for wave-band W.

Changes in the red edge spectral position and the inflection point can be determined from this approximation. Spectral flat profiles (either plateaus or troughs) have a derivative value of "0" while negative derivative values represent a decreasing slope value with increased wavenumber. Positive values are indicative of an increasing spectral slope with concurrent wavelength increases. Changes in the inflection point and slope steepness can be determined from a plot of the first derivative approximation (Figures 3 and 4). First derivative "red-edge" plot were derived for the control (healthy) and stressed sites.

1. Site 1
Figure 3, the approximation of the first derivative for site 1, was plotted for the 604-800 nm spectral region. The chlorophyll well can be seen at ~675 nm while the IR plateau is at ~730 nm. Both the stressed and the healthy derivative values coincide for much of the red-IR region, with no obvious wavelength shift noted between the plotted values.

2. Site 2
Figure 4 represents a plot of the 604-800 nm first derivative approximation for site 2. No red edge-shift is visible between the healthy and the stress site.

C. Moisture Stress Index (MSI)
A moisture stress index (MSI) was calculated for the two combination of sites. The MSI has been shown to be a relative measure of canopy moisture content (Miller, et al., 1990; Rock, et al., 1986). The MSI is computed as the ratio:

$$R_{1650} / R_{850}$$

where R is the radiance value for the spectral wavelengths centered at 1650 nm and 850 nm respectively. The sensitivity of the MSI is related to total canopy water content. Sites 1 and 2 MSI ratios were different. Site 1 control MSI was 0.0743 while the stress MSI value is 0.0766. Moisture stressed vegetation canopies would have a higher ratio value than a non-stressed canopy site. Although the site 1 stressed MSI value is expectedly higher, the MSI for the site 2 stress is lower than the MSI site 2 control (0.0734 control vs. 0.0677 stress).

III. RESULTS
Our initial assessment of AVIRIS data collected over control (healthy) and stressed Ponderosa pine stands in the Sierra Nevada of California indicates that some spectral differentiation is possible. For site 1 there is a consistent, expected spectral differentiation between the control and stressed sites evident from the spectral plots (Figure 1). This differentiation includes a stressed spectra that exhibits an increased blue-green to red trough (chlorophyll well) response and a decreased IR shoulder and IR response. There is a unique, strong peak and spectral differentiation of the stress and control site occurring at ~1440nm. This is probably due to a malfunctioning detector. Further investigations are

planned. The strongest spectral separability of the stress and control sites composing site 1 occurs at 820-860nm and 1003-1023nm.

For site 1, there is no evident shift in the "red-edge" inflection point between the stressed and the control site. Although a spectral shift would be expected, it is probable that it is undetectable given the AVIRIS spectrometer A bandwidths if 9.6nm. It has been noted that the "red-edge" spectral shift, representative of variations in leaf (needle) chlorophyll concentrations may occur at levels of only 5-9nm (Baret, et al., 1990). It is likely therefore that the small levels of noted stress would not be evident with AVIRIS band sensitivities.

The MSI calculated for site 1 indicated a stress index value of 0.0766 and a control index value of 0.0743. The relative difference is small, and may not be statistically significant for these site condition determinations.

For site 2, the spectral profile for the stressed and control Ponderosa pine sites is not consistent with expected results. The stressed canopy spectra track similar to the control spectra from the blue-green thru the red trough (chlorophyll well). In the near-IR, the stressed spectra have a higher radiance profile than the control site spectra. This continues thru 2336nm.

No "red-edge" spectral shift is visible in the approximated first derivative plots, for reasons similar to those discussed above for site 1. And, similar to the spectral profile for site 2, the MSI ratios are not consistent with the expected results. The stressed MSI ratio was slightly lower than the control MSI ratio values.

We postulate that the unexpected spectral characteristics for site 2 control/stress are the result of variations in the aspect and slope terrain characteristics, coupled with stand characteristic differences. Given the N/NW aspect of the site 2 control, a lower IR response would be expected due to an increased shadow presence. The control site is also located on a steeper slope profile than the stressed site. The mix of size classes, with an inclusion of larger trees casting shadows on smaller tree crowns, also affect the spectral homogeneity of the site. Even though the control site has an 80% crown closure (20% crown openings with understory complexes), the crown openings are effectively masked by a combination of the larger tree shadow zones and less direct solar illumination, given the N/NW aspect and steeper slopes. These factors combine to lower the overall spectral characteristics of the site. Another factor contributing to the higher IR response of the stress site (site 2) is the mixing of size classes evident on aerial photography. Upon closer examination of the stand, some small size class pines composed large sections of the area. These smaller size class timber stands were more homogeneous and had less apparent crown openings. Due to this even-age stand characteristic, there was little or no dominant larger trees casting shadows on neighboring crowns. This condition would lead to a higher IR response than the older, more open crown, N/NW facing, steeper control site. Although the stress site had 35-40% evident crown canopy damage, unlike site 1, the damaged (stressed) canopies were scattered throughout the site. Without any large, contiguous regions of stress, spectral differentiation would be difficult given the spatial resolution (20 meters) of the AVIRIS data. For site 1, damaged crowns were more tightly clustered, and were spectrally significant for the averaged site spectra. These conditions would preclude the accurate spectral separation of our site 2 control/stress stands.

IV. CONCLUSIONS

The use of AVIRIS hyper-spectral scanner data for discriminating moisture/beetle stress in Ponderosa pine communities appears promising. Shortcomings in our selection of our site 2 control/stress stands led to inconsistent spectral characterizations of stress/non-stress. Given the narrow spectral shift of the "red-edge" (on the order of 5-9nm), for discriminating needle chlorophyll content, AVIRIS data, with 9.6nm band-widths, does not appear to be an effective tool. The use of the MSI may prove beneficial, but a larger sample size for statistical purposes would be necessary to substantiate our findings. Initially, a differentiation between the control and stress sites is evident from the spectral profiles for site 1. The strongest differentiation occurs in two spectral regions: a 5-band area composed of 820-860nm, and a 3-band area from 1003-1023nm.

We encountered problems in the selection of a truly homogeneous control and stress site. Those problems were further compounded by the fact that our sites were located at the lower elevation limits of the Ponderosa pine communities in this area, and, Ponderosa pine, a drought -resistant species, may not show a significant biophysical change (stress) until moisture deprivation is much greater. Given our new knowledge of these constraints, our focus will be on developing a better understanding of the complicated biophysical and environmental factors that govern vegetation spectral characteristics. This hopefully will enable us to quantify change in forest health. In those regards, AVIRIS, and future planned hyper-spectral systems, will have great utility in the science community.

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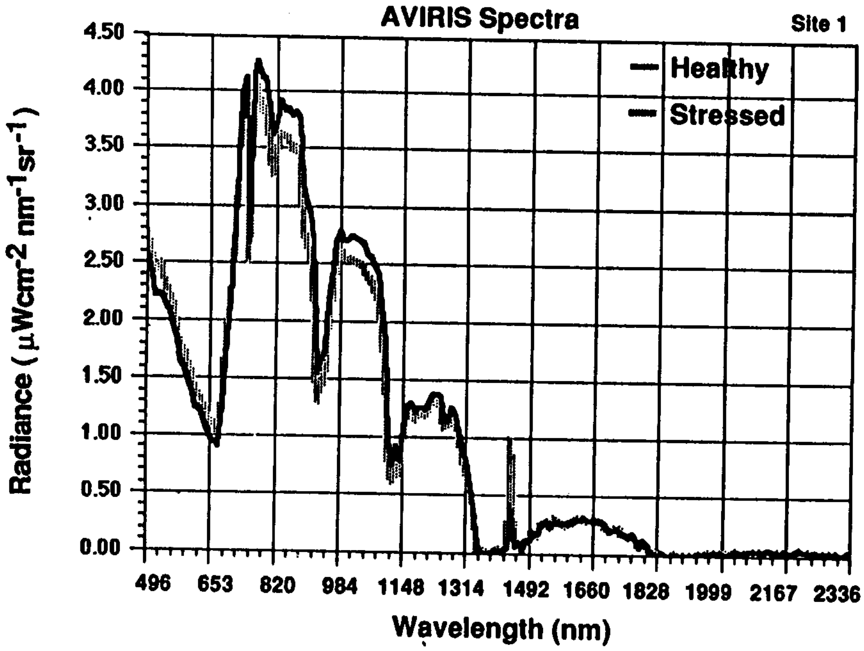

Figure 1. AVIRIS spectra for healthy (control) and stressed site 1; Ponderosa Pine stand. Reduced spectral range of 496 - 2336 nm.

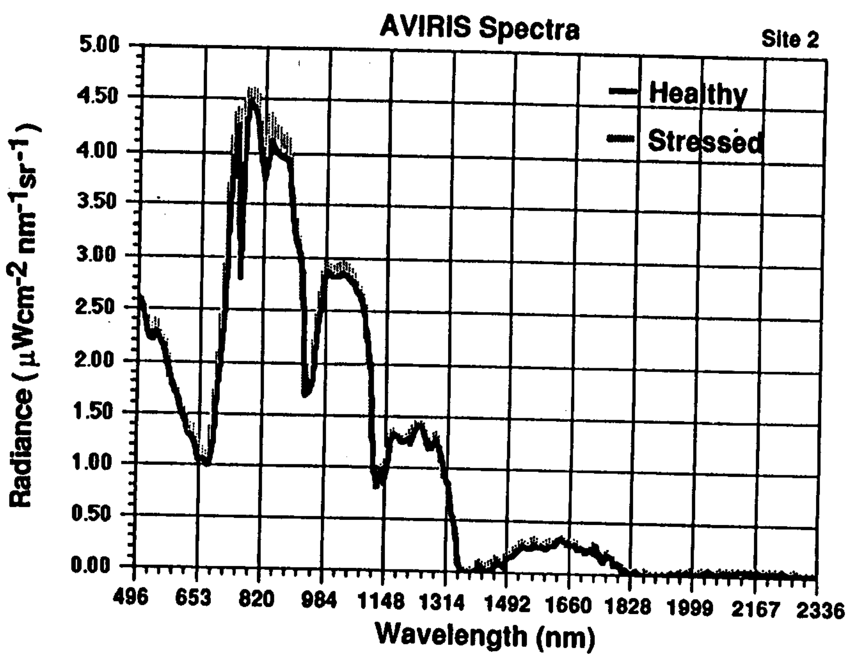

Figure 2. AVIRIS spectra for healthy (control) and stressed site 2; Ponderosa Pine stand. Reduced spectral range of 496-2336 nm.

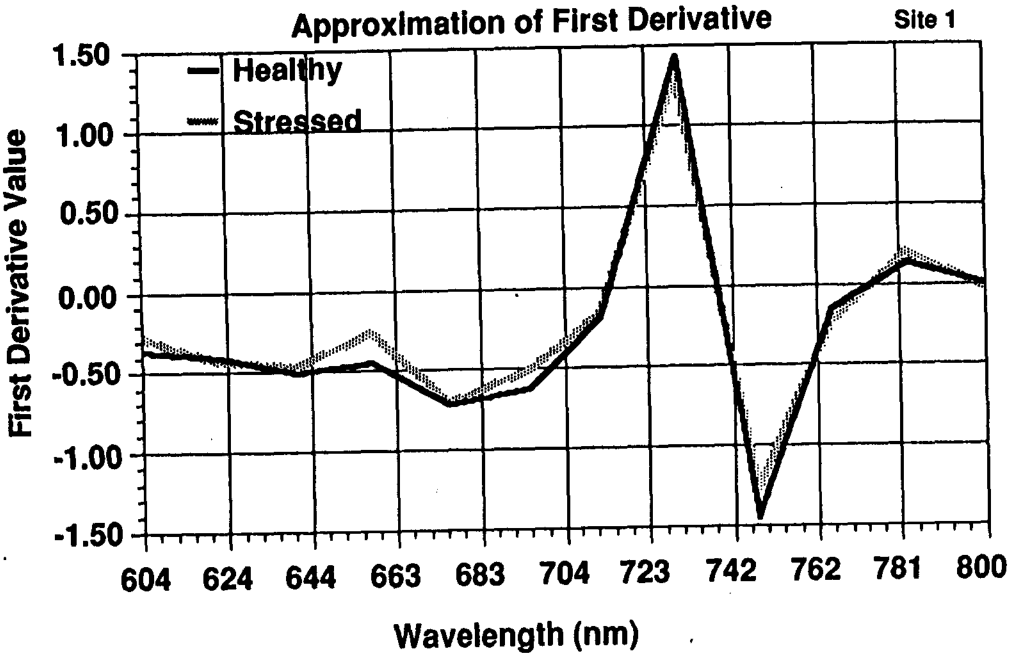

Figure 3. First Derivative Approximation plot for site 1; healthy/stressed Ponderosa Pine stand. Spectral range of 604-800 nm.

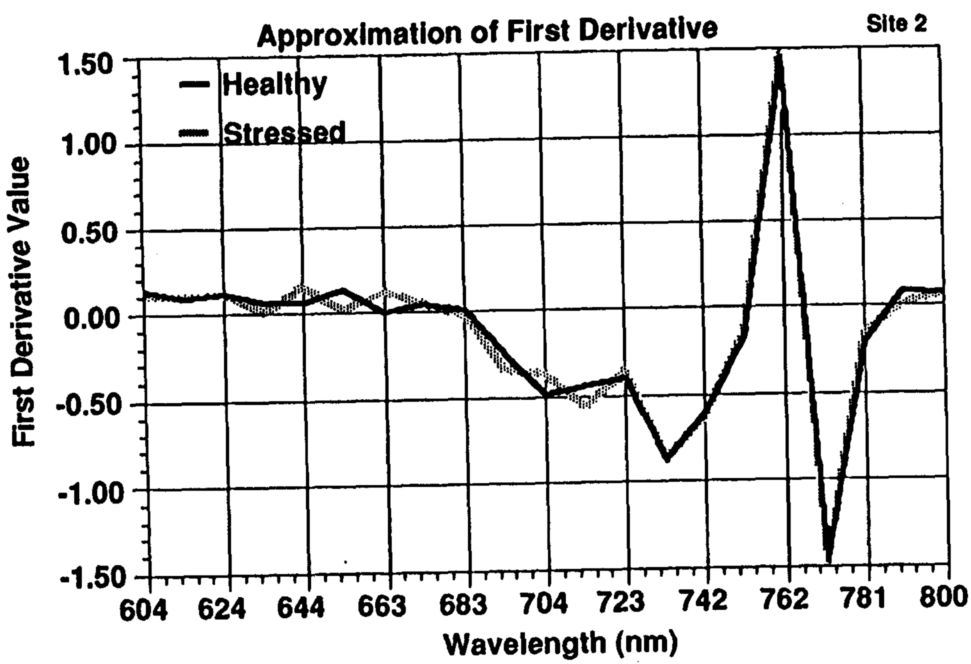

Figure 4. First Derivative Approximation plot for site 2; healthy/stressed Ponderosa Pine stand. Spectral range of 604-800 nm.