Dynamics Beyond the NIR for the Vegetation Index: A Test Case of Various Sample Spectral Signature of Differing Leaf State of Health in the Shortwave Spectrum Bands

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ABSTRACT: We report in this paper the results of spectroradiometric measurement in determination of the complete spectral signature of sample leafs with distinct and differing quality conditions by obtaining their response in the visible wavelengths (VIS), at near infrared (NIR) to the shortwave (SW) bands. Here we refer to the dynamics beyond the NIR as the extended range for the spectral response of the instrument from 1000nm to 2500nm. At these bands they indicate their relative reflectance and absorption values that translates to the quantification and indications of health of cell structure, water content, leaf biochemical, protein lignin, and celluse as well of the presence of nitrogen content. We obtained the numerical result by simple graphical analysis from the spectral plots at certain wavelengths for the vegetation index of interest.The reflectance values from 1510nm will yield the Normalized Difference Nitrogen Index (NDNI) where nitrogen concentration and overall biomass in foliage could be indicated. At 1754nm the Normalized Difference Lignin Index (NDLI) estimate the relative amounts of lignin contained in vegetation canopies. At 2000nm to 2200nm range the Cellulose Absorption Index (CAI) quantifies exposed surfaces that contain dried plant material and has absorption present that could indicate strong presence of cellulose. Canopy water content vegetation indices were also calculated from the response in the NIR with SW to provide an indication of the measured amount of water contained in the canopy. The Normalized Difference Water Index (NDWI) reflectance, which occurs at 857nm and 1241nm is known to be strongly related to the plant water content. This is interpreted to the effect that with higher water content often indicates healthier vegetation.The Moisture Stress Index (MSI) is sensitive to the effects of drought or catastrophic wetness increases in leaf water content at the absorption around 1599nm as well at 819nm and 1649nm that describes the Normalized Difference Infrared Index (NDII) values which uses a normalized difference formulation instead of a simplec ratio, with the index value increase with increasing water content. When compared with those spectral response in Landsat 8 OLI of 8 bands and MODIS of 36 bands, it showed that the required response were not present. These spectroscopy based measurements will serve for the purposes in the agricultural development efforts that could result in improved processes in agricultural crop management, plant canopy monitoring, and in the quantifying stressed vegetation .

1 INTRODUCTION

In the usual measurement of vegetation relative reflectance, the analyst concerns oneself of obtaining relative reflectance of the sample leaf or spectral signature of a canopy of the absorption in the visible bands Blue, Green, Red and where the invisible light are reflected in NIR (near infrared). For usual measurement of vegetation vigor the Normalized Difference Vegetation Index (NDVI) only requires the aforementioned bands. However, the complete the spectral signature would extend beyond 1000nm to as far as 2500nm in those bands hence, an entirely new set of vegetation indices are defined. In this paper we performed laboratory hand measurements of sample leafs selected with a-priori health condition based on observation and field experience.

1.1 The complete vegetation spectra resulting from light interaction mechanism from VIS, NIR and the SWIR

In Figure 1 we show a practical plot from a healthy leaf obtained by hand held instrument (ASD Fieldspec © Spectroradiometer) done in house. We reference to this actual measurement to show the three important ranges of bands for spectral response of the plant leaf. A color bar for purposes of visualization of spectral colors in the visible range is shown as inset. In the first part the VIS (Visible range) (380nm-740nm) it is where the B-G-R spectral colors are present. In this range it is known that the leaf exhibit the absorption response in the Blue and Red Band and the reflection in the Green band hence also known as the chlorophyll bump in these area. At this shorter and higher frequencies (4-7.5 $\times 10^{14}$ Hz) wavelengths (750 - 400 nm) and at some higher quantum energy (1.65-3.1 eV) than that of NIR and SWIR (Hyperphysics 2016), the VIS section of the spectra is describing graphically the mechanism in the leaf pigments in their chlorophyll absorption. At the level of visible light interaction with matter. The primary mechanism for the absorption of visible light photons is the elevation of electrons to higher energy levels with many available states. The visible radiation is able to provide the photons absorbed by matter to an electron level transition alone and thus no ionization ever take place.These VIS bands when IR and SWIR bands are included comprises the complete bands which a full signature can be visualized (Shaw,G.A., Burke,H.K., 2003).

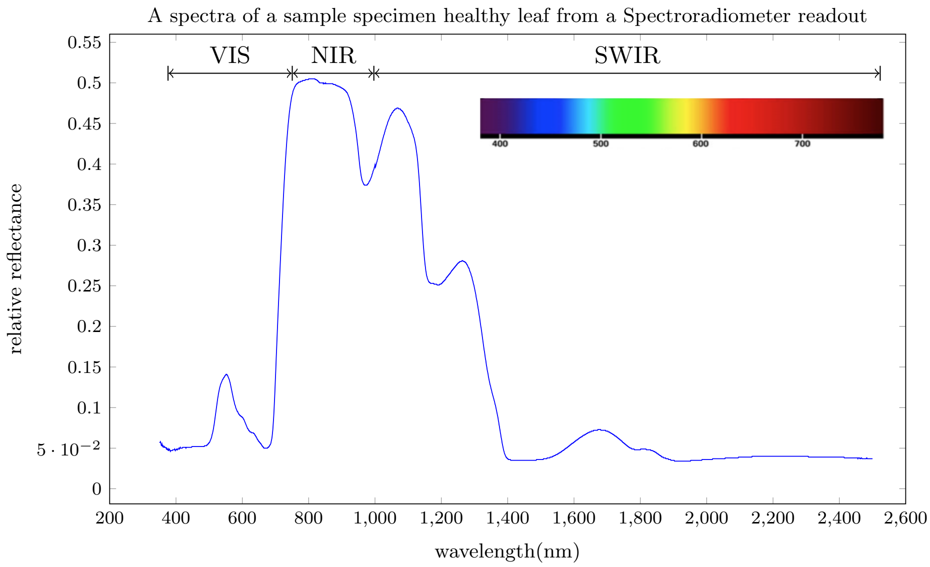

Figure 1: The complete spectra of a leaf taken from a specimen plant is shown from 350nm-2500nm showing band region of interest from the Visible, NIR and Shortwave IR the visible color scale is shown inset

Near infrared (NIR) since it is adjacent to the visible spectrum that extend up the the low frequency at the Red band with frequencies .003-4 $\times 10^{14}$ Hz. For healthy vegetation and leaf, this region is where the highest reflectance occurs and where leaf or vegetation cell structure will be of interest as primary mechanism acts at this level. In contrast with VIS which absorbs Blue and Red radiation and partially reflects Green spectral colors, near infrared is at the level of light interaction with matter acts to set molecules into an overtone vibrations since having higher quantum energies (0.0012-1.65 eV) at wavelengths (0.8-2500nm). At these bands molecules can absorb certain resonant frequencies i.e. the frequency of absorbed radiation matches the transition energy of the group that vibrates. Infrared radiation can lead to molecular vibration that can cause heating and depth penetration, these overtone vibrations maybe different according to the molecule that absorbs it giving specific vibrational modes and degrees of freedom that also depend on molecules being linear and non-linear after (Stuart,B., 2004).

The range (0.8-2.5μm) with the longer wavelength what is called far infrared is shown in the Figure 1 as SWIR (Short Wave Infrared) which was adapted following remote sensing usage other than from chemistry; particularly those that would concern with Landsat 7 ETM+ and Landsat 8 OLI where the full bands have their discrete bands dedicated to IR and SWIR. Commercial spectrometers are commonly starting from 350nm, 400nm and ends at 1000nm (USB Ocean Optics US) while those that extends from it are called Spectroradiometers (ASD Fieldspec US) instruments that covers everything from 350nm to as far as 3500nm.The mechanism for SWIR vibrational modes are the same as those already described for NIR. In the SWIR the response of the vegetation are descriptive of water content, the leaf biochemical, protein lignin and cellulose. In the following pages we detail the calculations for a select vegetation indices for our purpose.

2 MEASUREMENT SET-UP AND WORKFLOW

The measurement of the complete spectra of experimental sample specimens begin with identification of various stages and condition of health state of the plant leafs. The classified leafs are then labeled and marked and sequenced for for hand held test. The instrument (ASD FieldSpec ©Spectrometer) is calibrated using the white sulfur standard for calibration and background subtraction. The leafs then are measured and the measurements are logged on a computer. They are processed by an spreadsheet program and plotted. The plots are used to calculate by graphical manner to obtain the the vegetation index of interest. The results provides a baseline for establishing the signatures of afflicted plants, they are recorded and archived until the next opportunity to get newer samples. Optional but not required is the comparison of the results when the spectra is plotted over the Landsat 7 ETM+ or in Landsat 8 OLI and determine the relative spectral response from their shortwave bands. The basic set-up is shown in Figure 2 below:

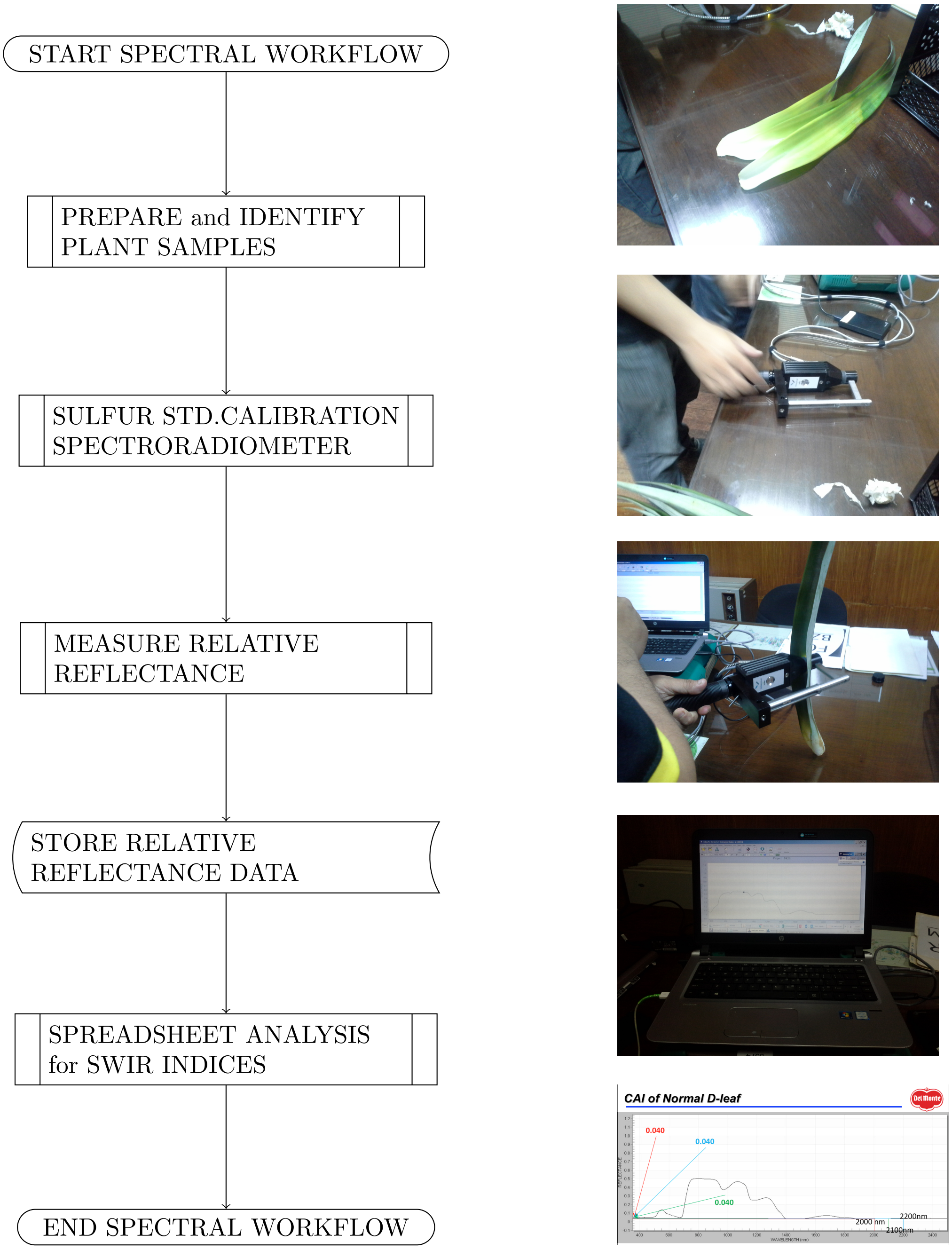

Figure 2: The steps for the measurement the complete spectra of the leaf from 350nm-2500nm that included VIS, NIR and SWIR regions

3 RESULTS AND DISCUSSION

We present the following results from the calculation of selected IR vegetation indices that are beyond the 1000nm band. The definition and formulas are given in Table 1 as well as the indication of possible range and typical values to expect for green vegetation. A representative graphical solution is provided mainly for the sample that are normal and then followed with those samples that indicates a known deviation manifested by their leaf features these specimen have been coded in Table 3.

3.1 Selected IR Vegetation Indices Definitions and Formulas

The definitions and formulas of the selected vegetation indices were all obtained obtained and condensed from a white paper after (Harris Geospatial 2016) and is depicted in the Table 1 below:

Table 1: Selected Vegetation Indices for the Shortwave Frequencies

Definition	Formula	Range Limits
Normalized Difference Nitrogen Index	$NDNI = \frac{\left[log\frac{1}{1510nm} - log\frac{1}{1680nm}\right]}{\left[log\frac{1}{1510nm} + log\frac{1}{1680nm}\right]}$	0..1, 0.02..0.1(green veg.)
Cellulose Absorption Index	$CAI = 0.5(2000nm + 2200nm) - 2100nm$	-3..≥4, -2..+4 (green veg.)
Moisture Stess Index	$MSI = \frac{1599nm}{819nm}$	0..≥3, 0.4..2 (green veg.)
Normal Difference Infrared Index	$NDII = \frac{(819nm-1649nm)}{(819nm+1649nm)}$	-1..+1, 0.02..0.6 (green veg.)
Normalized Difference Water Index	$NDWI = \frac{(857nm-1241)}{(857nm+1241nm)}$	-1..+1, -0.1..0.4 (green veg.)
Normalized Difference Lignin Index	$NDLI = \frac{\left[log\frac{1}{1754nm} - log\frac{1}{1680nm}\right]}{\left[log\frac{1}{1754nm} + log\frac{1}{1680nm}\right]}$	0..1, 0.005..0.05 (green veg.)

3.2 Summary of results of SWIR Vegetation Indices from selected samples

In order to facilitate the determination of these values in a long list of 350nm - 2500nm and their one to one correspondence with measured reflectance; we take note the fact that one sample measurement translates to 2150 rows by 2 columns for each spectral signature. By this column vector arrangement the data is search by use of "VLOOKUP" function by the spreadsheet program e.g. =VLOOKUP(L2,$A$2:$B$2152,2,FALSE) where the $A$2 is the column of frequencies and $B$2152 is the column of corresponding relative reflectance and the L2 contains the cell for which what wavelength to look for in the lookup table.The basic spreadsheet structure is show in Table 2 below:

Table 2: Spreadsheet structure for measurement data from 350nm-2500nm

wavelength(nm)	rel.reflectance
350	0.070
351	0.069
352	0.068
353	0.067
:	:
:	:
2497	0.034
2498	0.034
2499	0.033
2500	0.033

In Table 3 below we summarize the numerical results obtained from the spectral signature data for the specimen as tagged and identified by physical observation.

Table 3: Selected Vegetation Indices numerical result from Shortwave Frequencies

Specimen Tag	NDNI	CAI	MSI	NDII	NDWI	NDLI	Characteristic Effect
NRD-Leaf	0.1124	-0.0003	0.1376	0.7580	0.2822	0.0448	normal healthy leaf
PHY-Leaf	0.1597	0.0002	0.1512	0.6895	0.2426	0.0582	compounds effect in leaf
MBW-Leaf	0.1419	-0.0001	0.1576	0.7198	0.2469	0.0522	color change in leaf
YLW-Leaf	0.1750	0.0002	0.1403	0.7219	0.2407	0.0606	color change in leaf
WIT-Leaf	0.1548	0.0540	1.3297	-0.1612	-0.1208	0.0405	drying effect in leaf

3.3 Characteristic spectral signatures results from known physical effects

We show the spectral plots of selected type of leaf characteristic for each of the identified samples with a-priori knowledge of health and vigor as they tagged and coded. The following Figures 3,4,5,6,7 that follows below are representative spectra of the characteristic effects.

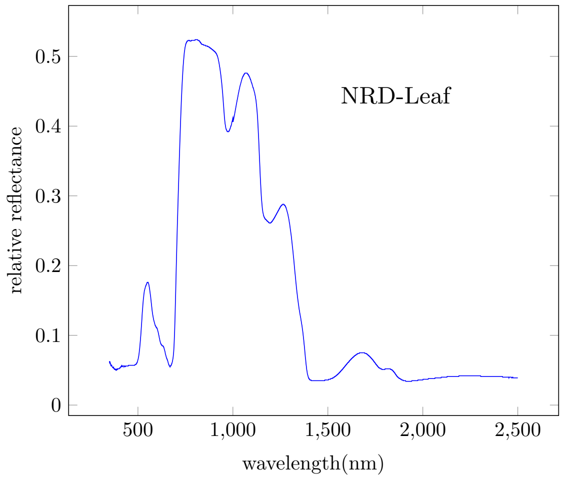

Figure 3: Spectral signature for a normal healthy leaf response from 350nm-2500nm

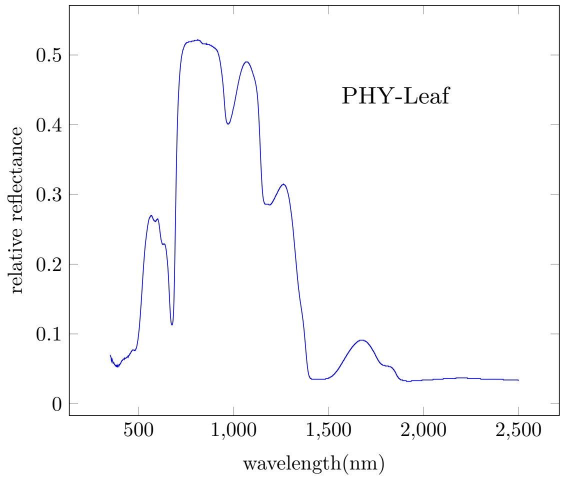

Figure 4: Spectral signature of a leaf showing possible indication of effect by a compound on plant

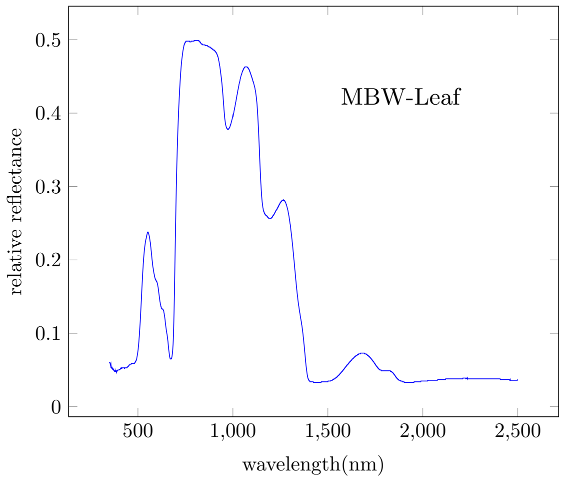

Figure 5: Spectral signature for affected leaf

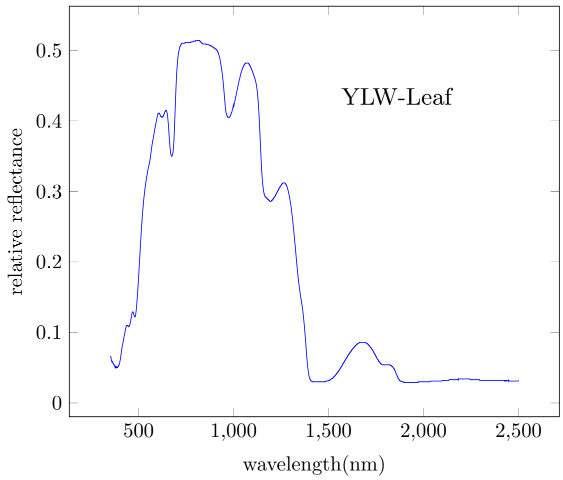

Figure 6: Spectral signature of a color change in leaf

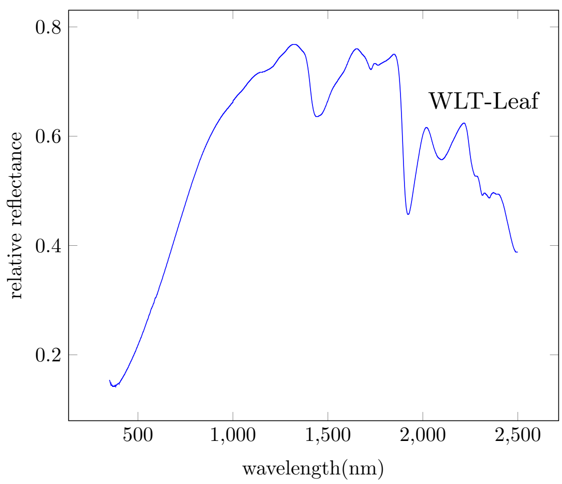

Figure 7: Complete spectral signature from dried leaf

3.4 Results from comparison with Landsat 8 OLI SWIR1 and SWR2 bands

We show the complete Landsat 8 OLI Bands in Figure 8 and while in Figure 9 we only show the infrared bands including the Cirrus band. We overlay the spectral signature of a healthy leaf on the IR bands and obtain those frequencies that would be usefull for the calculation of the vegetation indices as have been done in the previous section. We summarize these results in Table 4.

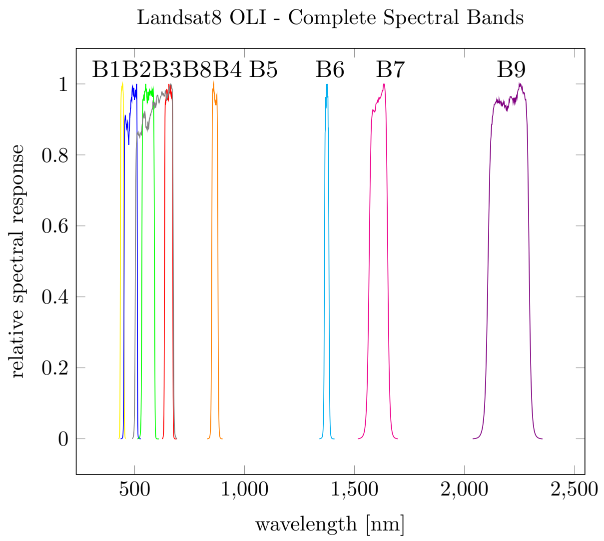

Figure 8: The Landsat 8 is a 30m resolution 5 visible bands and 4 invisible bands with a 15m panchromatic band (Band 8)

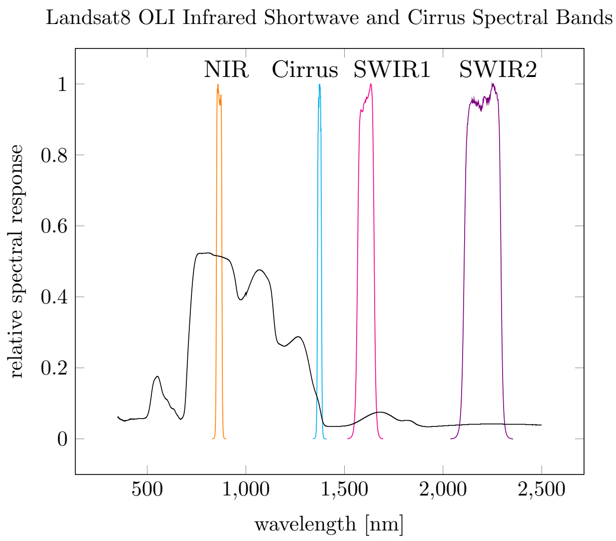

Figure 9: The Landsat 8 OLI Bands IR, SWIR1, SWR2 and Cirrus with the overlay of NRD-Leaf spectral signature

Table 4: Landsat IR Bands with overlay of spectral signature of healthy leaf

Landsat 8 Band	Range(nm)	Rel.Reflectance at intersection
Band 5	829-900	0.516@851nm, 0.512@879nm
Band 6	1340-1409	0.120@1360nm, 0.050@1389nm
Band 7	1515-1697	0.044@1560nm, 0.074@1663nm
Band 9	2037-2355	0.039@2068nm, 0.041@2311nm

We see that with definition given in Table 1 when we consider the IR Bands in Landsat 8 OLI will not be able to yield results using the formulas since the frequencies of interest either lie outside their spectral response or either only one of the two needed wavelengths are available for calculation. These are specially having no response at 1510nm and 1680nm for NDNI, at 2000nm and 2200nm for CAI, 819nm for MSI and NDII, 1241nm for NDWI, 1680nm and 1764nm for NDLI. We conclude that on the extended range beyond NIR the vegetation indices cannot be compared with Landsat 8 OLI bands. However, at the VIS range up to 800nm becomes possible since at these bands both the ASD FieldSpec © and Landsat 8 OLI have spectral response present as shown by (Woranut ,2011) using Moderate Resolution Imaging Spectroradiometer (MODIS) bands.

3.5 Results from comparison with MODIS Land, Cloud and Aerosols Band

We compare also the results from the ASD Spectroradiometer © with the Moderate Resolution Imaging Spectrometer after (MODIS Specification, 2016) from a subset of its 36 bands particularly those first seven bands herein tabulated below in Table 5.

Table 5: Landsat IR Bands with overlay of spectral signature of healthy leaf

MODIS sub-bands	Range(nm)	Primary Use
Band 1	620 - 670	Land/Cloud/Aerosols Boundaries
Band 2	841 - 876	Land/Cloud/Aerosols Boundaries
Band 3	459 - 479	Land/Cloud/Aerosols Properties
Band 4	545 - 565	Land/Cloud/Aerosols Properties
Band 5	1230 - 1250	Land/Cloud/Aerosols Properties
Band 6	1628 - 1652	Land/Cloud/Aerosols Properties
Band 7	2105 - 2155	Land/Cloud/Aerosols Properties

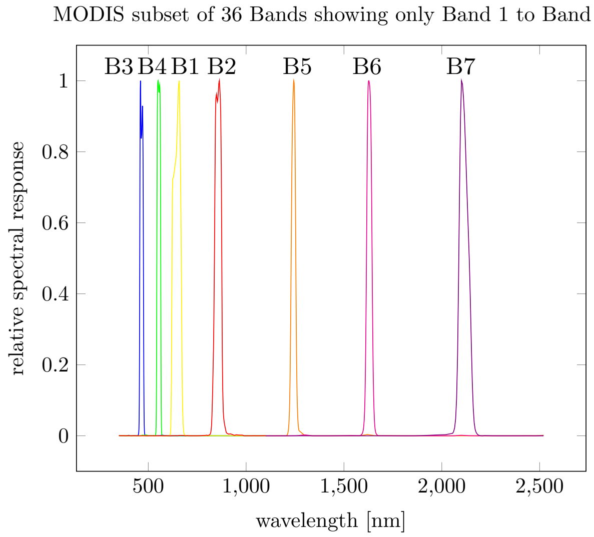

Figure 10: MODIS subset bands uses Band 1 through Band 7 with the B3, B4 and B1 being the visible bands

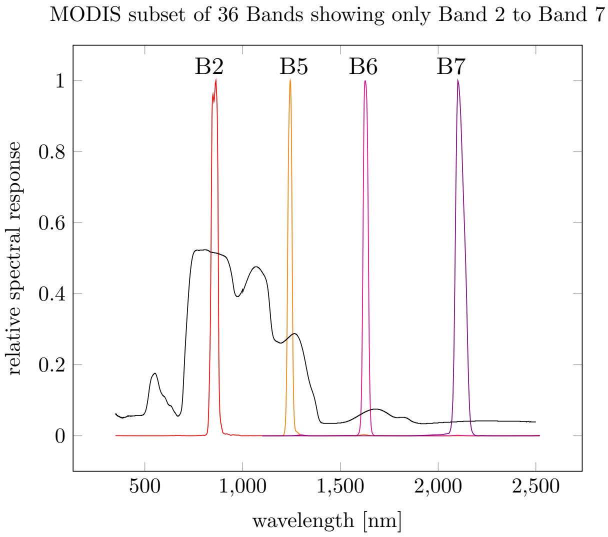

Figure 11: MODIS with only IR Bands overlaid with spectral signature of a healthy plant

When we consider MODIS spectroradiometer bands in Figure 10 and Figure 11 for the calculation the IR vegetation indices we arrive at the same problem in obtaining the required frequencies in band in MODIS as for NDNI, CAI, MSI, DNII, NDWI and NDLI hence, even at a smulated response using these bands we cannot have a correlation at specific bands as with the field instrument.

4 CONCLUSIONS AND RECOMMENDATIONS

The results from the hand held spectroradiometer instrument measurement operating from 350-2500nm for known samples have shown values as expected in the typical green vegetation figures. It is also true as well as for those expected range for those otherwise. However, the lack of the proper spectral response from both Landsat 8 OLI and with MODIS have not provided a validation and comparative analysis of results between the instrument and the simulated response using their IR available bands. It maybe possible to make adjustments to the definition for the IR vegetation indices at those specific frequencies for which they were defined so that the Shortwave bands in Landat 8 OLI can useful and well as the MODIS of the many groups of 36 bands available. An experimental verification maybe needed to observe at a molecule level if the energies of a new selection of the wavelength will have quantum energies that will result to vibration of atoms to warrant it to be give reflectance at those select frequencies.At the end of this experimental work we have also produced the spectral signatures of known states of leaf health.

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