REMOTE SENSING DERIVED COMPOSITE VEGETATION HEALTH INDEX THROUGH INVERSION OF PROSAIL FOR MONITORING OF WHEAT GROWTH IN TRANS GANGETIC PLAINS OF INDIA

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KEYWORDS: Vegetation Health Index, MODIS, BRDF, PROSAIL, Wheat, EVI, Leaf Area Index, Chlorophyll, Equivalent Water Thickness.

ABSTRACT:

The present study proposed a composite vegetation health index (VHI) derived from Leaf area index (LAI), Chlorophyll content (Cab) and equivalent water thickness (Cw) of wheat crop in Trans Gangetic Plains of India. The wheat growing areas of the study area were retrieved from time series 16 days MVC MODIS Enhance Vegetation Index (EVI) data. The LAI, Cab and Cw were retrieved from MODIS reflectance (MOD09) through inversion of radiative transfer model, PROSAIL using Look Up Table (LUT) approach. The results revealed that LAI, Cab and Cw were very well retrieved with RMSE 0.3892, 4.307 and 0.0063 respectively. R^2 values for all the three parameters were significant and were found to be 0.904, 0.917 and 0.894 respectively. A composite VHI was developed from LAI, Cab and Cw, values. Based on the VHI, wheat growing area in study region was divided into four zones. Wheat growing areas having VHI ranging from 0-0.25 and 0.25- 0.5 are classified as poor growth conditions. Wheat regions having VHI values from 0.5 to 0.75 and above 0.75 were classified as good and very good conditions respectively. The classified VHI map was compared with yield map of the study area and was found highly correlated.

1. INTRODUCTION

Research on crop growth monitoring has played a crucial role in many policy decisions on development in agriculture.

Basic requirement for crop growth monitoring is an efficient tool for retrieving different biophysical parameters and its reliability and development of a composite index from retrieved crop parameters. Estimation of leaf area index (LAI), total chlorophyll content (Cab) and vegetation water content (Cw) can not only assist in determining vegetation physiological status and health, but also were found useful for the detection of vegetation stress, photosynthetic capacity, and productivity (e.g. Tucker, 1980; Carter, 1994; Boegh *et al*., 2002; Zarco-Tejada *et al.*, 2003). Remote Sensing has been found to be potential and vital source in estimating these parameters. Different methods to estimate canopy biophysical variables from reflectance data have been developed and can be grouped into two approaches such as (1) statistical approach and (2) physical process based approach (using Radiative Transfer Models). Using statistical approach, many researchers have developed empirical relationships between vegetation indices (VIs) and canopy biophysical variables. The equations defining such empirical and semi-empirical relationships not only vary in the mathematical form (Linear, power, Exponential, etc) but also in their empirical coefficients, depending upon the cultivars, regions and the data normalizations approaches adopted. These methods are very simple but the accuracy of biophysical variable estimation may be quite low. They are suffering from severe limitations due to the lack of physics introduced in the retrieval technique and the small amount of radiometric information they can exploit. Alternately, physical modeling approach is based on the inversion of canopy reflectance models that describe the radiative transfer in the canopy as a function of biophysical variables which characterize the canopy architecture and the optical properties of vegetation elements and the soil. In the mid-80s, the anisotropic properties were observed to be crucial for diagnosing plant canopy functioning. Enhanced understanding of the physical processes that govern the interactions between light and the canopy elements, bi-directional canopy reflectance (CR) models emerged for its inversion issues on multidirectional data in the early 90s for retrieval of biophysical parameters (Goel, 1987).

Inversion of bidirectional canopy reflectance (CR) models emerged as a promising alternative for retrieval issues (Goel 1989; Myneni *et al*, 1991; Liang and Strahlar, 1993; *Tripathi et al*, 2006). The space borne instruments like POLDER, ADEOS, MISR, TERRA, *etc* were designed to study both the spectral and directional characteristics of the earth surfaces. This trend depicts one of the scientific stakes to come in remote sensing, which is to take advantage of both the spectral and the directional signatures of vegetation in order to retrieve the biophysical parameters.

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In this paper, an attempt has been made to retrieve LAI, Cab and Cw of wheat crop grown in Trans Gangetica Plains of India from MODIS Surface Reflectance Product (MOD09) and develop a composite vegetation health index.

2. STUDY AREA AND DATA USED

2.2 Study Area

The study area is Trans Gangetic Plains of India covering whole states of Punjab and Haryana, Delhi and two districts of Rajasthan having geographical extent between 72°38'54.44" to 77°36'11.74" East longitude and 27°39'19.38" to 32°30'26.85" North longitude (Figure 1). Wheat is widely grown rabi crop in this region which is the test crop in the present study.

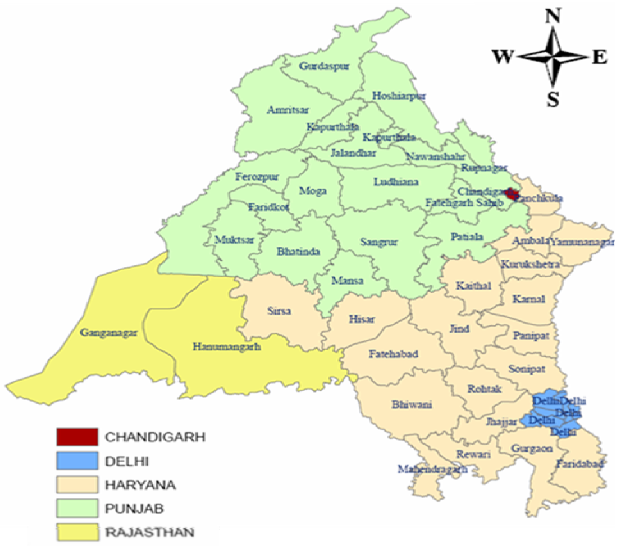

Figure1. Map of the Study Area – the Trans-Gangatic Plains of India with District and State/Union Territory Boundaries

2.3 Satellite Data Used

The satellite data used for retrieval of biophysical parameters was MODIS Surface reflectance data product (MOD09) of Feb 10 -20, 2008 acquired from the EOS Data Gateway. The MOD 09 is 8-day composite product, computed from the MODIS Level 1B land bands 1, 2, 3, 4, 5, 6, and 7 (centered at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm, respectively) and spatial resolution is 500m. The product is an estimate of the surface spectral reflectance for each band as it would have been measured at ground level if there were no atmospheric scattering or absorption (Vermote *et al.*, 1999). The times series 16 days maximum value composite of MODIS EVI product (500m spatial resolution) were also used for the period of Nov., 2007 to May, 2008 for estimating wheat growing regions.

2.4 Ground Truth and Spectral Data Collection

Field visit was conducted during February 10-20, 2008, in the wheat growing regions of the study area only with the purpose to collect spectral reflectance data of wheat crop and bare soil using ground held spectroradiometer (ASD-FS[3], 350-2500 nm), *in situ* measurement of LAI using canopy analyzer and other biophysical parameters of the wheat crop. This period is the peak vegetative stage of the wheat in the region and thereby was appropriate for ground truth collection and use of the satellite data for different biophysical parameters retrieval. Wheat leaf samples were also collected for chlorophyll content estimation and also equivalent water thickness in the laboratory. The ground truth was conducted using handheld GPS (Leica GS 5) and 190 locations (latitude and longitude) of the sample collection were noted down.

3. METHODOLOGY

3.1 Mapping of Wheat Growing Areas

For discrimination of wheat growing areas, the times series 16 days maximum value composite of MODIS EVI product (500m spatial resolution) was used for the period of Nov 2007 to May 2008. The products were masked for Trans Gangetic region using its vector layer and stacked together and necessary correction of the temporal EVI profile was done using FASIR (Fourier Adjusted Sun Zenith Angle Corrected Interpolated and Reconstructed) written in IDL. The corrected time series EVI data product was classified for estimation of wheat growing areas using spectral angle mapper classification technique (Kruse *et al*., 1993). This method was found to be better than many conventional classification approaches as this method is not affected by solar illumination factors, because the angle between the two vectors is independent of the vectors length.

3.2 Radiative Transfer Model

The radiative transfer model PROSAIL (Jacquemoud, 1993) was used for simulation of bi-directional reflectance and retrieval of biophysical parameters through its inversion. The PROSAIL model was developed combining PROSPECT (Jacquemoud and Barret, 1990) and SAIL model (Verhoef and Bunnik, 1981). PROSAIL considers the detailed information on leaf optical properties and also accounts for hotspot effect. The model computes canopy reflectance in a particular wavelength band as a function of (1) canopy structural parameters such as leaf area index (LAI), leaf mesophyll structure parameter (N), mean leaf inclination angle (tl), leaf size/crop height (sl); (2) biochemical parameters like chlorophyll-a+b concentration (Cab) and water content (Cw); (3) viewing geometry parameters- solar zenith, view zenith and relative azimuth angle; and (4) soil reflectance.

LAI was measured *in situ* using canopy analyzer, total chrolophyll (Cab) and Equivalent water Thickness (Cw) were measured following standard procedure.

3.3 Calibration of the Model and Inversion

A representative measured wheat spectra (in wavelength range 350 to 2500 nm) were prepared for calibration of the model. For simulation, input parameters were defined based on field survey and literature. The parameters like LAI (l), chlorophyll content (Cab), equivalent water thickness (Cw), dry matter content (Cm) of the wheat crop and sun geometry (sun zenith θs, and azimuth Φs) of the study area were taken from the mean of the field measured values. The sun zenith and azimuth values of the study area were computed using geographical position (longitude and latitude) and time of the spectral observation (i.e. saved in spectral files collected in the field) through a programme written in IDL. The hemispherical soil reflectance (rsoil) for the model was taken from the field measurements. The sensor parameter (isat) was taken as 0 for spectroradiometer and hotspot parameter (ihot) as 0 for non hot spot position. Non hot spot position was preferred as the field measurement was done irrespective of the sun's positions. The rest input parameters such as mean leaf inclination (degree) (tl), leaf internal structure parameter (Vai), leaf size/crop height (sl), horizontal visibility (vis) were taken from the literature.

The simulated reflectance was generated for varying LAI, chlorophyll, equivalent water thickness, biomass and hotspot parameter separately at certain interval while keeping all other variables constant in the model. The simulated and measured reflectance for each parameter was compared and RMSE was computed. That value of the parameter was regarded as the optimum, for which the RMSE was minimum between measured and simulated reflectance spectra.

3.4 Sensitivity Analysis of the PROSAIL Model

Sensitivity analysis of PROSAIL model was carried out for three parameters namely, leaf area index, chlorophyll content and equivalent water thickness which were to be retrieved through inversion of the model. For assessing the sensitivity of the model all the parameters were kept constant at calibrated model values as discussed above except the parameter for which sensitivity analysis was being carried out. Chlorophyll content was varied between 5 to75 µg cm^{-2} at an interval of 5, leaf area index was varied between 1.6 to 9.4 at an interval of 0.2 and equivalent water thickness was varied between 0.002 to 0.127 cm at an interval of 0.005cm. Band wise coefficient of variation was calculated for all the simulated reflectance's generated to do the sensitivity analysis of these three parameters. The calibration and sensitivity analysis of the PROSAIL was done with 100 sample points selected randomly. Rest 90 points were used for validation of the retrieval products.

3.5 Inversion of PROSAIL for Parameter Retrieval

The PROSAIL model was found to be very much suited for inversion due to the reduced number of parameters in it and high speed of simulation of multiangular spectra (Casa and Jones, 2004). The parameters for which the inversion was attempted were LAI (l) and chlorophyll content (Cab) and equivalent water thickness (Cw). The inversion procedure involved creation of Look Up Table (LUT) of the simulated reflectance and matching of the measured with LUT values using merit function (Nilson and Kuusk, 1989). For inversion purpose, simulated reflectance of MODIS bands 1, 2, 3, 4, 5, 6, and 7 (centered at 648 nm, 858 nm, 470 nm, 555 nm, 1240 nm, 1640 nm, and 2130 nm, respectively) were only used. Iterative minimization of the merit function (Press *et al*, 1986) was programmed and run in MATLAB and different biophysical product images (of LAI, Chlorophyll and equivalent water thickness) were created from the output of the inversion programme using ENVI image processing software.

3.6 Development of the Composite Vegetation Health Index (VHI)

The aim of developing vegetation health index (VHI) was to give a single value to the vegetation condition on the basis of three retrieved parameters (leaf area index, chlorophyll content and equivalent water thickness), which are most important for assessing the vegetation condition. Being these parameters are in different units and value ranges, standardization was done and transformed to a single scale *i.e.* zero to one. Equal weightage was allotted to each parameter and the index score was obtained with a linear sum aggregation function. The function consists of the weighted sum of three parameters i.e. leaf area index (LAI), chlorophyll content and equivalent water thickness divided by the sum of the weights as given in equation (1).

$$VHI = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1} w_i} \qquad (1)$$

Where, w_i = weightage given to the i^{th} parameter and x_i = i^{th} parameter.

4. RESULTS AND DISCUSSION

The wheat mask was generated using the times series 16 days maximum value composite of MODIS EVI product (500 m spatial resolution) for the period of Nov., 2007 to May, 2008 using spectral angle mapper classification approach and given in Figure 2. The wheat mask generated through this classification technique was used as defined study region further in the study for parameter retrieval and development of vegetation health index. However, the result has limitation in considering small patchy wheat fields mainly found in hilly region and some part of southern Punjab due to course resolution satellite data though SAM classification has mostly taken care of subpixel variation in the wheat coverage.

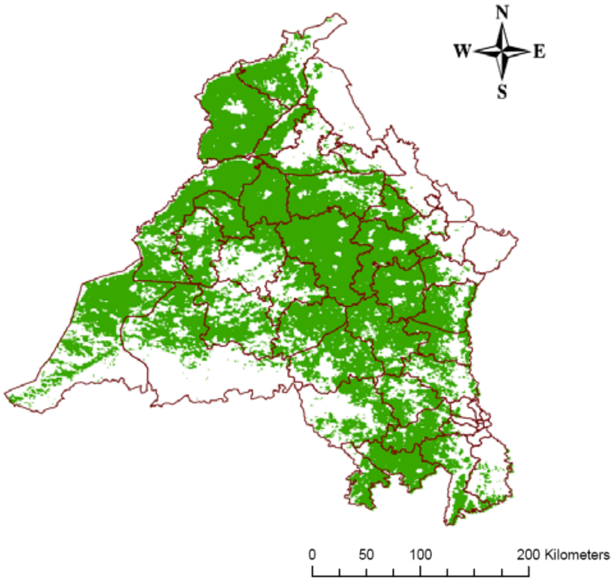

Figure 2. Wheat Mask of the Study Area Generated from Time Series 16 Days MVC of MODIS EVI Data of 2007-08

4.1 Calibration and Sensitivity Analysis of PROSAIL

Model was calibrated with respect to its input parameters and optimum value for parameters were found based on minimum RMSE computed from observed and simulated reflectance of the model. The optimum value considered for LAI, Cab, Cw, hot spot parameter, and dry biomass (Cm) are 4.5, 48 μgcm^{-2}, 0.0180 cm, 0.49, and 0.013 g cm^{-2} respectively.

The sensitivity analysis of LAI, Cab and Cw were done and coefficient of variations (CoV) were calculated and plotted to observe at which wavelength, the model was more sensitive to the variation in LAI. In case of LAI, it was observed that CoV was negligible between wavelength range of 745 nm to 1300 nm (Figure 3). Beyond 1300 nm, CoV sharply increases and reaches upto 40% at 1450 nm again comes down and then reaches to 94% at 1930 nm. CoV was highest i.e. 97% at 2495 nm. Overall LAI effect was seen through the entire wavelength range of 400 to 2500 but more dominant over higher wavelength range from 1850 to 2500 nm.

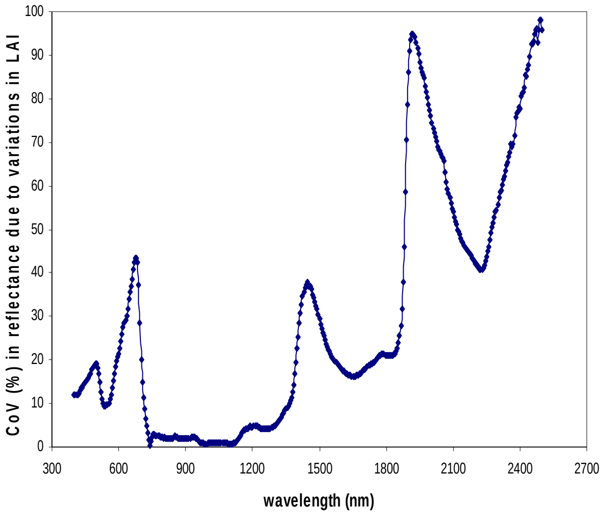

Figure 3. Coefficient of Variation of Simulated Reflectances at Varying LAI of Wheat in Wavelengths Ranging from 400 to 2500 nm

Effect of Cab values on the reflectance were found to be confined to only in the visible range *i.e.* from 400 nm-700 nm. As expected, increasing Cab causes significant reductions in the visible waveband reflectances. This was observed that CoV was significant only in the wavelength range of 400 nm to 765nm which is very obvious as the crop reflectance at this region is dominantly governed by pigments (Figure 4). Beyond 765 nm, there was no variations in the generated simulated reflectance values with varying Cab values.

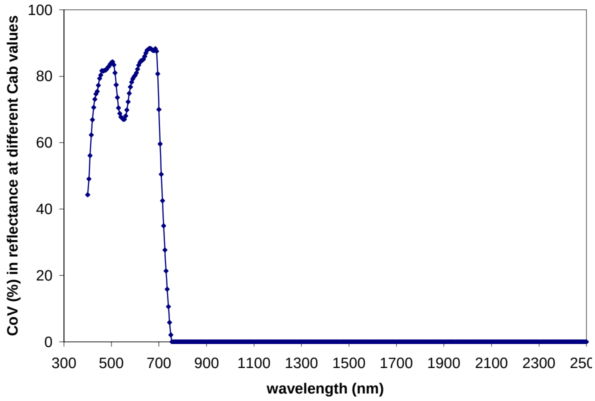

Figure 4. Coefficient of variation of simulated reflectances at varying chlorophyll content (Cab) in wavelengths ranging from 400 to 2500 nm

In case of Cw, it was observed that CoV was negligible between wavelength range of 400 nm to 940 nm. However CoV was higher beyond 940 nm and highest peaks were found to be 1425 at 1885 nm *i.e.* water absorption bands and crop reflectance at these regions were majorly governed by leaf water content (Fig.6).

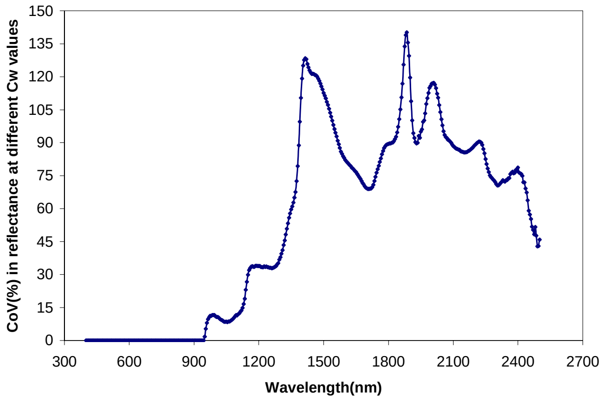

Figure 6. Coefficient of variation of simulated reflectances at varying leaf equivalent water thickness values (Cw) of wheat in wavelengths ranging from 400 to 2500 nm

4.2 Prosail Model Inversion for Retrieving Parameters

Inversion of PROSAIL model was done to retrieve LAI, Cab and Cw of Wheat crop in the Trans Gangetic Plains of India. LUT approach using merit function was used for model inversion and parameters were retrieved from MODIS reflectance data. These derived images of LAI, Cab and Cw are given in Figure 7 (a), (b) & (c) respectively. These values were compared with observed ones (corresponding values of 90 random locations) and predictive accuracy was evaluated with RMSE values. Results revealed that LAI, Cab and Cw, were very well retrieved and comparable with measured values with RMSE error 0.3892, 4.307 and 0.0063 respectively. R^2 values for all the three parameters were significant and were found to be 0.904, 0.917 and 0.894 (Figure 8 a, b & c), for LAI, Cab and Cw respectively, when retrieved values were compared with measured values.

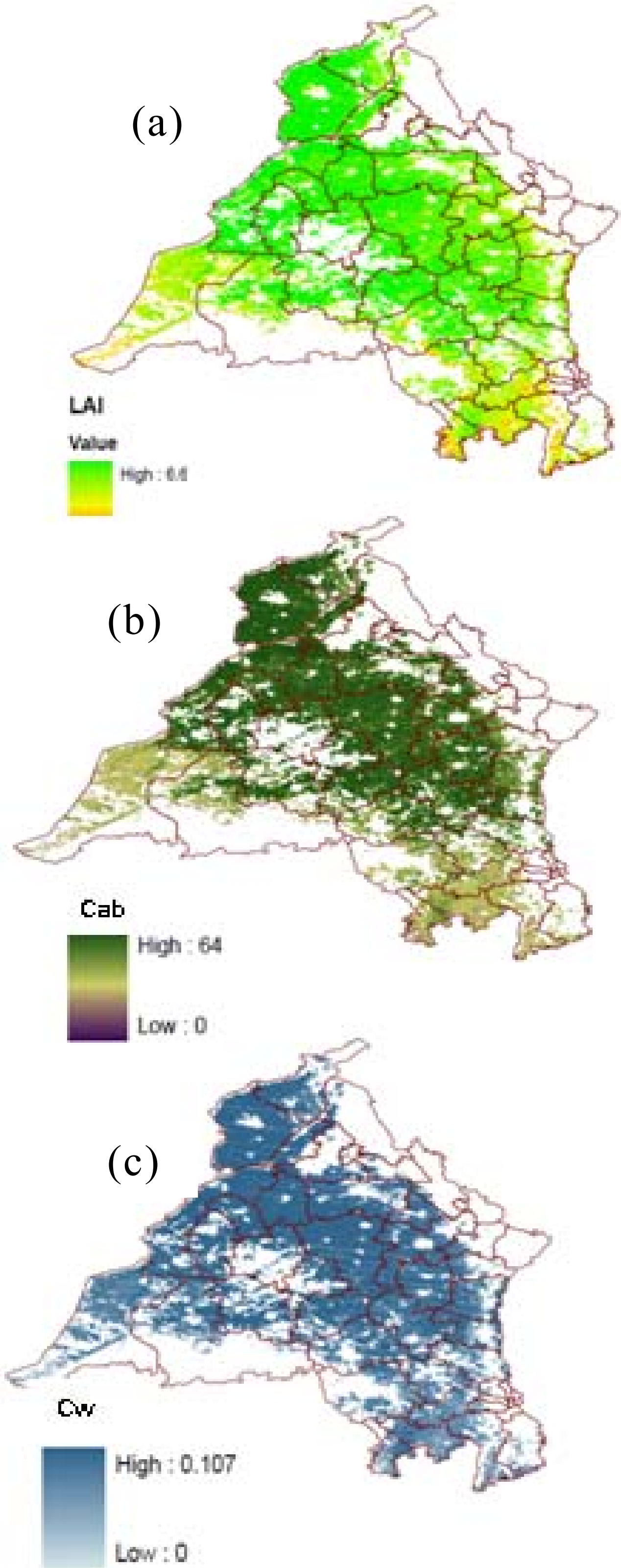

Figure 7. Retrieved (a) LAI, (b) Total Chlorophyll Content (Cab) and (c) Equivalent Water Thickness (Cw) Product of Wheat Through Inversion of the PROSAIL Model

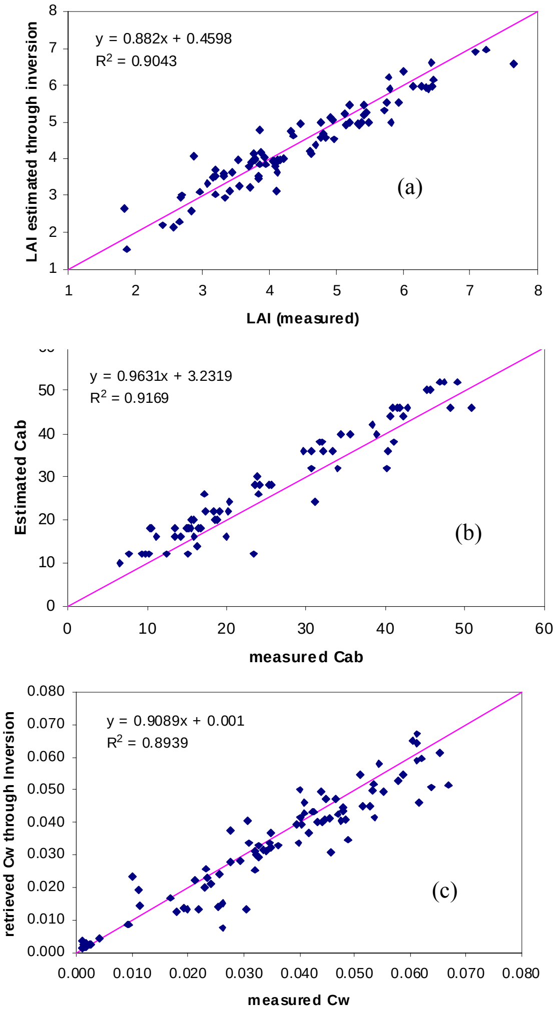

Figure 8. Comparisons of PROSAIL Inversion Retrieved Wheat (a) LAI, (b) Cab and (c) Cw with their Measured Values Respectively (with 1: 1 line)

4.3 Development of Vegetation Health Index (VHI)

The proposed VHI is a composite index was derived from most important three growth parameters such as LAI, Cab and Cw as shown in Figure 9. LAI has direct relationship with biomass and yield of the crop, Cab is majorly governed by nutrient (mainly nitrogen) which indicates indirectly N stress and Cw, reflects water status in the canopy and thereby water stress. The composite indicator considering all these three parameters may provide information about the vegetation health there by the index is named vegetation health index which can be used to prioritize zones at regional scale yield enhancing site specific interventions. Since LAI, Cab and Cw retrieved through inversion were found to be more reliable the biophysical products of LAI, Cab and Cw derived through PROSAIL model inversion were used for the development of the vegetation health index. The VHI value obtained was ranging 0 to 1.

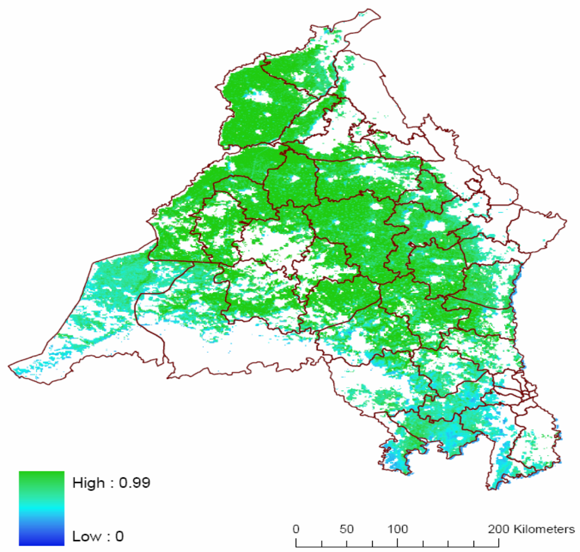

Figure 9. Vegetation Health Index Map of Wheat Crop Composited from LAI, Cab and Cw Products

4.4 Prioritization of the Region Based on VHI

Based on the VHI, study region was divided into four zones corresponding to four growth conditions of wheat crop. Wheat area with very poor growth conditions were having VHI ranging from 0-0.25 and 0.25- 0.5 for poor growth, 0.5 to 0.75 to good and above 0.75 for very good conditions (Figure 10). When the classified VHI map was compared with yield map of the study area. , it was observed that areas with higher VHI were also producing higher yields and *vice versa*.

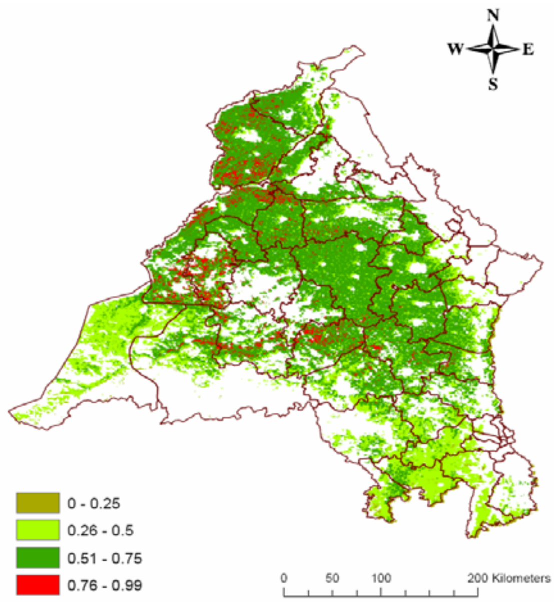

Figure 10. Zonation of the Wheat growing area of Trans-Gangetic Plains of India into four groups based on the Vegetation Health Index (VHI)

CONCLUSION

Basic requirement for crop growth monitoring is the efficient tool for retrieving different biophysical parameters and its accuracy or reliability. Study demonstrated potential of remote sensing data and radiative transfer model in retrieval of LAI, Cab and Cw at regional scale. Parameter retrieved can be directly used for crop growth monitoring and otherwise through developed VHI for site crop management practices. The very poor and poor VHI values zones can be further considered for site specific growth enhancing management practices.

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