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Developing Vegetation Health Index from biophysical variables derived using MODIS satellite data in the Trans-Gangetic plains of India

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Abstract

Basic requirement for crop growth monitoring is the efficient tool for retrieving different plant biophysical variables and its accuracy or reliability. In the present study, statistical approach is used to retrieve the three biophysical parameters i.e. leaf area index (LAI), Chlorophyll content (Cab), and leaf equivalent water thickness (Cw). Normalized Difference Vegetation Index (NDVI), Red Index (RI) and Normalized Difference Water Index (NDWI) were used to retrieve LAI, Cab and Cw respectively. Study area was Trans-Gangetic plain comprising of whole Punjab, Haryana, Chandigarh, Delhi and some parts of Rajasthan. Field measurements were done at 190 locations. Spectral measurements (wheat crop and soil) with ground held spectroradiometer (FieldSpec3), LAI using Canopy Analyzer (LICOR-2000) and leaf samples were collected for further analysis in laboratory. Satellite data used was MODIS Surface Reflectance Product (MOD 09). Vegetation Health Index (VHI) was developed using the retrieved LAI, Cab and Cw and study area was categorized into four groups based on VHI.

Key words: Chlorophyll content, Equivalent water thickness, NDVI, Leaf area index, Vegetation health index

Introduction

Assessment of vegetation condition particularly caused by biotic or abiotic stress such as drought or pest infestation can be critical for countries where the economy is dependent on the crop harvest. Early assessment of yield reductions could avert a disastrous situation and help in strategic planning to meet demands. Basic requirement for crop growth monitoring is an efficient tool for retrieving different plant biophysical variables and its accuracy or reliability. Remote Sensing has been found to be potentially valuable in estimating these biophysical variables. The methods to estimate canopy biophysical variables from reflectance data are (1) Statistical approach and (2) Process based approach (using Radiative Transfer Models). Empirical or statistical approaches are based on observations of the spectral contrasts of reflectance and consist of fitting a relationship between reflectance and some biophysical variables, mainly by the use of vegetation indices (Tripathi et al., 2012).

Leaf Area Index (LAI) has been an important variable that is directly related to photosynthesis, evapotranspiration, and productivity of agro-ecosystems. Measurement of LAI in the field is very difficult, and requires a great amount of time and efforts. The mapping of LAI in large geographic area may be impossible when we rely on the field measurement. To solve this problem, there have been continuing efforts to develop methodologies to estimate LAI using remotely sensed data. Because of the obvious difference of the optical features between leaf and non-vegetative surface, it is possible to assess LAI by applying remotely sensed data.

The common approach has been used to correlate ground-measured LAI with the simple ratio or the normalized difference vegetation index (NDVI), and modified simple ratio (Leonard Brown and Chen, 1999). The normalized difference vegetation index was the most commonly used. Hui et al. (2003) indicated that there is a good linear correlation between LAI by ground measurement

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and NDVI calculated from Landsat ETM data. Increase in the amount of canopy chlorophyll, either through an increase in leaf chlorophyll content or leaf area index (LAI) will lead absorption well in vegetation reflectance spectra centred on 680 nm (Gitelson et al., 1996).

To estimate chlorophyll content of plant, the method of indices is generally used. Indices R_{NIR}/R_{700} and R_{NIR}/R_{550} for chlorophyll assessment were recently developed as a result of signature analysis of the reflectance spectra of two deciduous species (maple and chestnut) (Gitelson and Merzlyak, 1994a, 1994b; Gitelson et al., 1996) and of tobacco plant (Lichtenthaler et al., 1996). These indices allow for chlorophyll estimation in dark-green to yellow leaves within a wide range of pigment variation. It was reported also that the index *R760/R695* is a sensitive indicator of plant stress. Vegetation water content (VWC) is an important indicator in agricultural and forestry applications. The VWC could possibly provide information for agriculture that can be used to infer water stress for irrigation decisions, aid in yield estimation and in the assessment of drought conditions. At a whole-plant level, soil drought and leaf water deficit lead to a progressive suppression of photosynthtesis, and is associated with alterations in carbon and nitrogen assimilation (Zlatev and Lidon, 2012). The principle application to forestry is determining fire susceptibility (Pyne et al., 1996). The VWC is also used in retrieving soil moisture from microwave remote sensing observations. Ceccato et al. (2002 a, b) found that the short wave infra red (SWIR) channel was critical to estimating VWC and the near Infra red (NIR) channel was needed to account for variation of leaf internal structure and dry matter content variations.

Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Terra and Aqua earth observation system satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days. MODIS has a viewing swath width of 2330 km and views the entire surface of the Earth every one to two days. MODIS is playing a vital role in the development of validated, global, interactive Earth system models able to predict global change accurately enough to assist policy makers in making sound decisions concerning the protection of our environment.

Keeping all these in background this study was conducted with the objective of retrieving Leaf Area Index, chlorophyll and moisture content of wheat crop at regional scale from TERRA MODIS products using statistical approaches and to develop a composite vegetation health index.

Materials and Methods

The study area lies between 72°38'54.44"E to 77°36'11.74"E and 27°39'19.38"N to 32°30'26.85"N, with altitude varies between 590 to 3600 ft (180 metres to 1200 metres) above sea level, which covers whole states of Punjab and Haryana, Delhi and two districts of Rajasthan in India which is commonly known as Trans-Gangetic Plain (Figure 1).

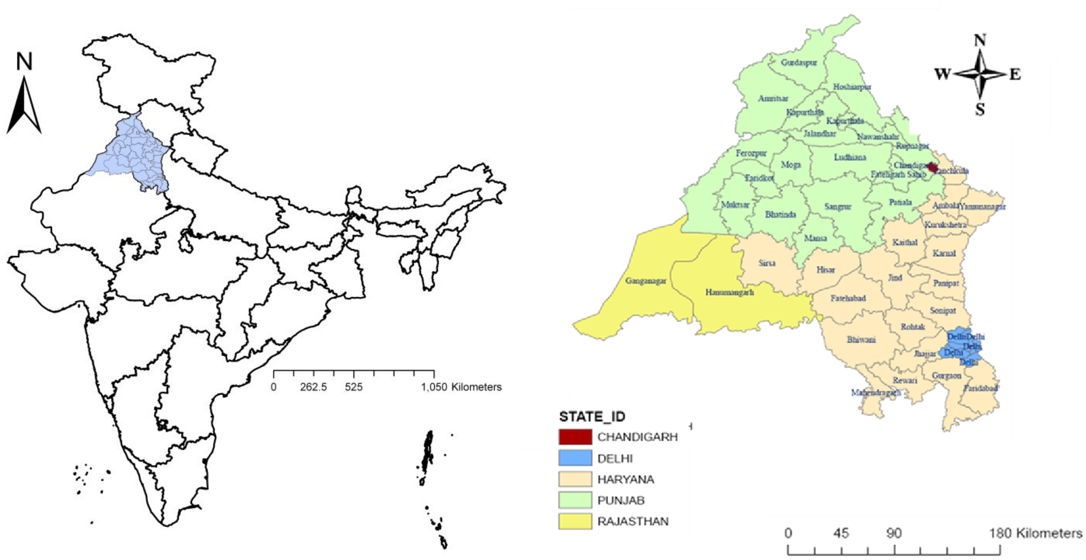

Figure 1. (a) Location of study area in the map of India. (b) Study area (Trans-Gangetic Plains) with district boundaries.

Satellite Data used

MODIS Surface reflectance data product (in the blue, green, red and near-infrared wavelength regions i.e. MOD09) were acquired from the EOS Data Gateway (https://wist.echo.nasa.gov/api/) Brief description of these products are given below

MODIS Surface Reflectance Product (MOD 09)

The MODIS Surface-Reflectance Product (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). The MODIS Level 1B (L1B) algorithm performs radiometric calibration of data from the MODIS sensors on the EOS-Terra and EOS-Aqua satellites. Input to L1B is the Level 1A (L1A) and geolocation data. L1A includes the raw digital counts from the sensor and telemetry data for each Earth-view pixel. The Level 1B Code generates data products containing calibrated radiances for all MODIS bands. 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).

Image Dimensions = 2400 x 2400 rows/columns
File Size = 50 – 500 MB
Resolution = 500 meters
Projection = Integerized Sinusoidal
Data Format = HDF-EOS
Composite MOD 09 product of the duration Feb 10 -20, 2008 was used for the present study. For satellite image processing ENVI 4.4 and ArcGIS 9.2 softwares have been used.

Ground Truth and and Spectral Data Collection

A field visit was conducted in early February, 2008 in the wheat growing regions of the study area with the purpose of in situ measurement of LAI using canopy analyzer (LICOR-2000), spectral measurement (wheat crop and soil) and other biophysical variables of the wheat crop. Wheat leaf samples were also collected for measurement of chlorophyll content and equivalent water thickness in the laboratory. The ground truth was conducted using handheld GPS (Garmin) and locations (latitude and longitude) of the sample collection points were recorded (Figure 2).

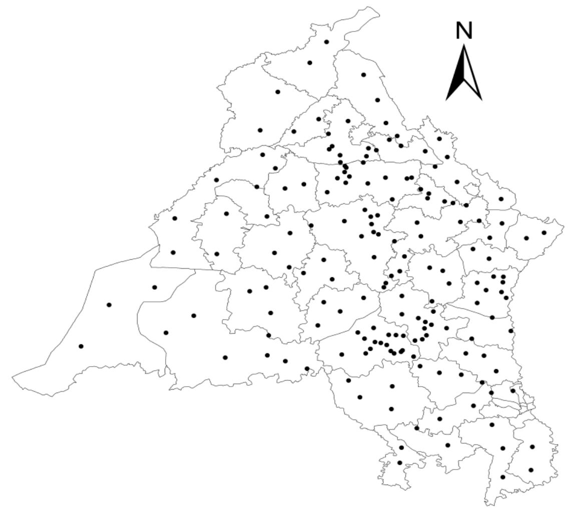

Figure 2. Ground truth locations acquired through hand held global positioning system in the Trans-Gangetic Plains of India.

Spectral Reflectance Data Collection

Spectral reflectance of wheat crop grown in different farmers' fields were collected using ASD Field Spec™ 3 ground held spectroradiometer having 25° Field of View (FOV) synchronizing with observation of other biophysical parameters. The spectral data has not been used for this particular study.

In situ - Leaf Area Index measurement

In situ LAI measurement was done in various farmers' field of the study area using canopy analyzer (LICOR-2000). The instrument was set to take four below canopy measurements and one above canopy measurements to estimate the LAI. Canopy analyzer (LICOR-2000) measures the gap fraction P(θ) in five zenith angle (θ) ranges with midpoints of 7°, 23°, 38°, 53° and 67°. LAI is determined by inverting simple radiative transfer model foliage information. This indirect LAI estimate specifically represents an effective leaf area index for the agricultural crops and an effective plant area index, including branch components, for deciduous forests. The assumption of a random spatial distribution of the leaves as made in the model inversion is generally satisfied for these crops. Where a nonrandom spatial distribution of canopy foliage is observed, an accurate description of gap size is essential to avoid large errors in LAI estimation (Chen et al., 1997; Gower et al., 1999).

LAI is calculated according to Gower and Norman (1991) from the LAI-2000 gap fraction measurements:

$$\mathrm{LAI} = 2\int_0^{\pi/2} \ln[1/P(\theta)]\cos\theta\sin\theta\,d\theta$$

LAI measurement was done in 190 locations having two measurements in each field.

Leaf Moisture Thickness

Equivalent leaf moisture thickness was calculated by using the expression

$$= \frac{(\text{Fresh weight - Dry weight})}{\text{Leaf Area}}$$

and expressed in gm cm^{-2} or cm.

Leaf chlorophyll content

Fresh leaf samples from different treatments were cut and 100 mg was weighed and chlorophyll was extracted by a non-macerated method equilibrating it with 10 ml *D*i *M*ethyl *S*ulf*O*xide (DMSO) in a capped vial and keeping in an oven at 65°C for about 4hrs. The decanted solution was used to estimate the absorbance at 645 and 663nm wavelength using Spectrophotometer Spectronic-20. The total chlorophyll content was calculated using the formula given by Arnon (1949).

$$\text{Total Chlorophyll content (mg/g of fresh weight)} = \frac{[20.2\text{x}A_{645} + 8.02A_{663}]XV}{1000XW}$$

Where,
A_{645} = Absorbance at 645 nm
A_{663} = Absorbance at 663nm
V = Final volume of chlorophyll extract in DMSO
W= Weight of plant sample

Spectral indices

The following vegetation indices have been derived using MODIS bands (Table 1).

Table 1. MODIS bands and their corresponding wavelengths.

MODIS Bands	Wavelengths (nanometer)
Band 1	620-670
Band 2	841-876
Band 3	459-479
Band 4	545-565
Band 5	1230-1250
Band 6	1628-1652
Band 7	2105-2155

Normalized Difference Vegetation Index

The traditional approach for LAI estimation using Vegetation indices is based on the combination of a chlorophyll sensitive band (typically the red band) and a band located in the high reflectance plateau of vegetation canopies (NIR band). The high canopy penetration ability of the NIR band makes it highly useful for tracking variations in biomass and LAI. Normalized difference vegetation index has been widely used for the retrieval of LAI as it combines the NIR band (ρ_{nir}) and red band (ρ_{red}) reflectances.

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}}$$

Red Index (RI)
It combines the NIR band (ρ_{nir}) and red band (ρ_{red}) reflectances.

$$RI = \frac{\rho_{nir}}{\rho_{red}} - 1$$

Red Index (RI) were evaluated for the estimation of total canopy chlorophyll concentration

The Normalized Difference Water Index (NDWI)

Gao (1996) NDWI was employed for the determination of vegetation water content. NDWI uses two bands centered at approximately 860 nm and 1240 nm and follows the simplicity of NDVI.

$$NDWI = \frac{\rho_{858} - \rho_{1240}}{\rho_{858} + \rho_{1240}}$$

where ρ_{858} is the MODIS NIR band centered at 858 nm and ρ_{1240} is the MODIS MIR band centered at 1240 nm.

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 parameters (leaf area index, chlorophyll content and equivalent water thickness) which are most important for assessing the vegetation condition.

The following four steps were followed for the development of vegetation health index:

1. Selection of variables
2. Transformation of the variables of different units and dimensions to a common scale
3. Assignment of weight or score to the variables
4. Aggregation of three variables to produce a final index

Transformation of the parameters of different units and dimensions to a common scale

Different vegetation health index parameters are expressed in different units. For example Chlorophyll content is expressed in µg cm^{-2}, equivalent water thickness in centimeters, and leaf area index is unitless. In other words, different parameters occurred in different ranges and were expressed in different units. To formulate the index, all the parameters were transformed into a single scale beginning with zero and ending at one. Linear stretching was performed on all the parameters, using the following formulae for rescaling.

$$DN'' = \left(\frac{DN - MIN}{MAX - MIN} \right)$$

Where,

DN'' = Digital number assigned to pixel in output image

DN = Original digital number of pixel in input image

MIN = Minimum value of input image, to be assigned a value of zero in the output image

MAX= Maximum value of input image, to be assigned a value of 1 in the output image

Assignment of weight to the biophysical variables

Since the three parameters i.e. LAI, Chlorophyll content and equivalent water thickness were equally important, equal weight of 1/3 was allotted to each of the three parameters for deriving the vegetation health index.

Aggregation of three parameters to produce a final index score. 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.

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

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

x_i = i^{th} parameter

Results and Discussions

Regression model for the retrieval of leaf area index

Normalized difference vegetation index (NDVI) was used for the retrieval of LAI using regression analysis. NDVI map was generated using the equations described above. The empirical approach based on exponential relationships was used to relate NDVI to ground measured LAI in the present study (Table 2). A regression analysis between NDVI and measured LAI was performed. Regression analysis between NDVI and measured LAI resulted in a R^2 value of 0.667 (Figure 3). The exponential model of NDVI-LAI relationship was used to generate LAI map (Figure 4). It was observed that R^2 value and RMSE between the ground measured LAI and estimated LAI through regression were 0.6759 and 0.5833 respectively.

Our results are in accordance with other researchers. Houborg and Eva (2008) found that LAI–NDVI relationships resulted in good agreements between estimated and measured LAI for barley, wheat and maize sites with an overall root mean square deviation of 0.74. Some researchers have observed low correlation between NDVI and LAI in numerous studies (Chen and Cihlar, 1996, Cohen et al., 2003; Turner et al., 1999). NDVI has been a popular index with which to estimate LAI across diverse systems, and numerous studies have noted a strong contribution of short wave infra-red band to the strength of relationships between reflectance and LAI (Brown et al., 2000; Cohen and Goward, 2004).

Regression model for the retrieval of chlorophyll content (Cab)

Red index (RI) was used for the retrieval of Cab using regression analysis. Red index map was generated using the equations described above. The empirical approach based on linear relationships was used to relate RI to measured Cab values (Table 2). The overall R^2 observed was 0.96 for RI–Cab relationship (Figure 5). The linear model using RI-Cab regression analysis was used to generate chlorophyll map (Figure 6). It was observed that R^2 value and RMSE between the ground measured Cab and estimated Cab through regression were 0.8515 and 5.2043 respectively.

Houborg and Eva (2008) compared estimates from the composited Cab map (generated thorough regression approach) with field measurements at different wheat, barley and maize sites which recorded a root mean square deviation of only 4.9 $\mu g\ cm^{-2}$.

Regression model for the retrieval of Equivalent leaf moisture thickness (Cw)

Regression analysis was performed between normalized difference water index (NDWI) and Cw for the retrieval of Cw. Normalized difference water index map were generated using the equations described above. The empirical approach based on exponential relationships was used to relate NDWI to measured Cw in the present study. A regression analysis between NDWI and Cw (measured) showed a R^2 value of 0.726 (Figure 7). The exponential model using NDWI-Cw was used to generate Cw map (Figure 8). It was observed that R^2 value and RMSE between the ground measured Cw and estimated Cw through regression were 0.73 and 0.01 respectively.

Table 2. Regression models developed for retrieval of Leaf area index, Chlorophyll content and Equivalent water thickness through regression of corresponding indices' with measured values.

S. No.	Parameter	Method	Regression equation	R^2 Value with measured parameter
1	Leaf area index	Regression with NDVI	Y = 1.835 exp (1.51 x)	0.68
2	Chlorophyll content	Regression with RI	Y = 4.45 x + 9.45	0.85
3	Equivalent water thickness	Regression with NDWI	Y = 0.23 x + 0.02	0.73

NDVI: Normalized difference vegetation index; RI:Red Index; NDWI: Normalized difference water index

Absorption by vegetation liquid water near 0.86 µm is negligible. Weak liquid absorption at 1.24 µm is present. Canopy scattering enhances the water absorption. As a result, NDWI is sensitive to changes in liquid water content of vegetation canopies. Normalized difference water index (NDWI) employing the MODIS mid-infrared band centered at 1.24 µm was much better candidate than enhanced vegetation index and NDVI for the estimation of vegetation water content (Houborg et al 2007).

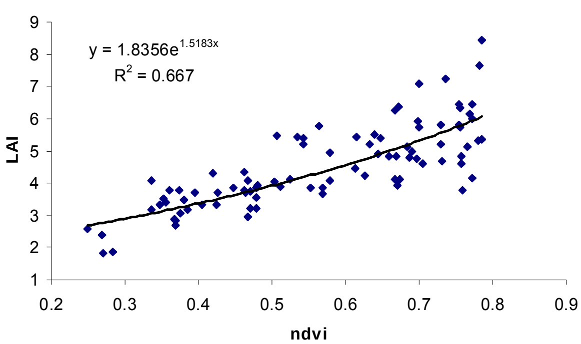

Figure 3. Regression relationship between the normalized difference vegetation index (NDVI) derived from MODIS data and the ground measured LAI.

Developing vegetation health index and zonation of the study area based on the VHI

The proposed VHI is a composite index was derived from most important three crop growth variables such as LAI, Cab and Cw. Leaf area index has direct relationship with biomass and yield of the crop. Chlorophyll content (Cab) is majorly governed by nutrient status (mainly nitrogen) of the plant which indicates indirectly N stress. Equivalent water thickness (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 for site specific interventions for enhancing crop yield. Since LAI, Cab and Cw retrieved using vegetation indices approach were found to be more reliable and hence used for the development of the vegetation health index.

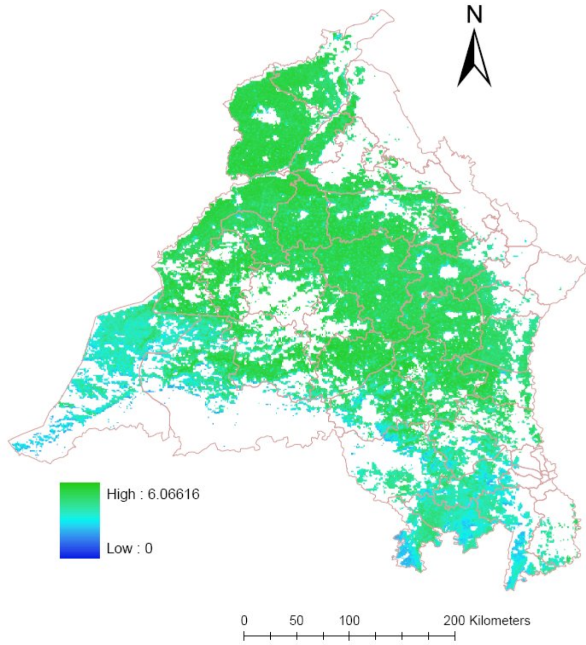

Figure 4. Leaf area index (LAI) map generated through exponential regression model between normalized difference vegetation index (NDVI) and ground measured LAI.

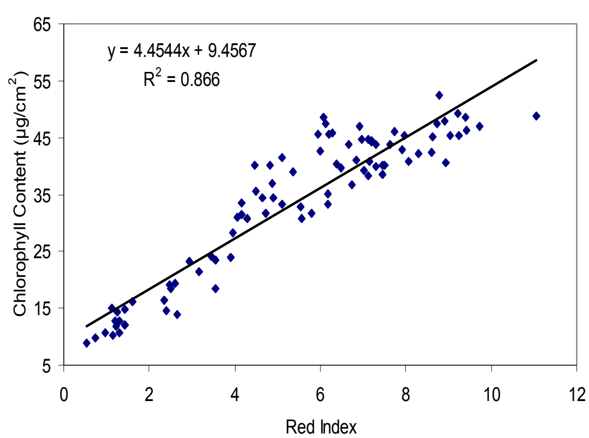

Figure 5. Regression analysis between chlorophyll content and MODIS Red Index.

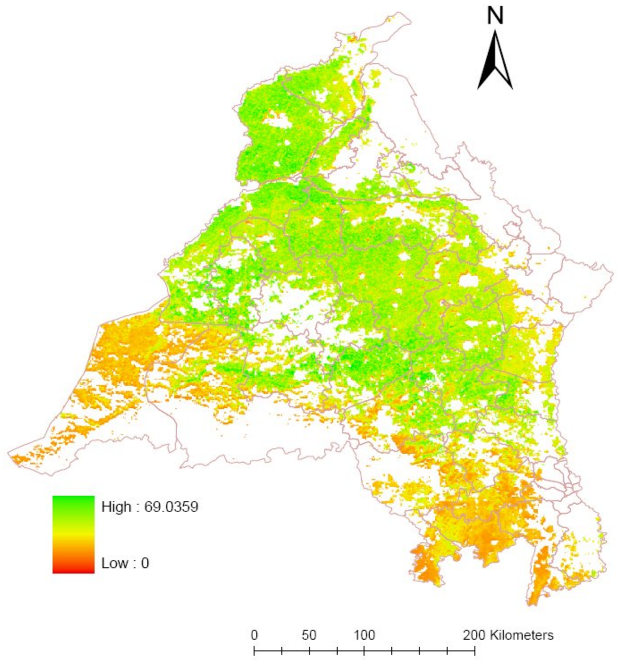

Figure 6 Chlorophyll Content (Cab) map (µg/cm2) retrieved through Linear regression model between measured Cab with Red Index.

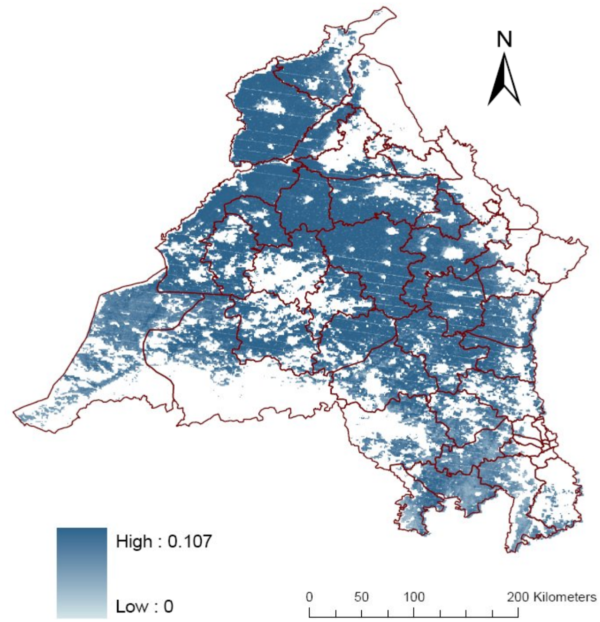

Figure 8 Leaf equivalent water thickness(Cw, in cm) map retrieved through regression model developed between normalized difference water index (NDWI) and measured Cw.

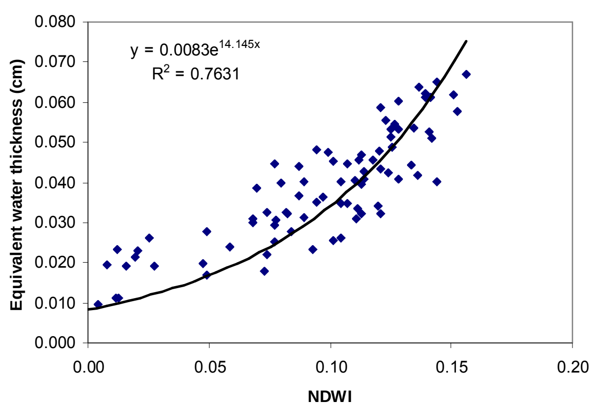

Figure 7. Regression analysis between normalized difference water index (NDWI) derived from MODIS data and measured equivalent water thickness (cm).

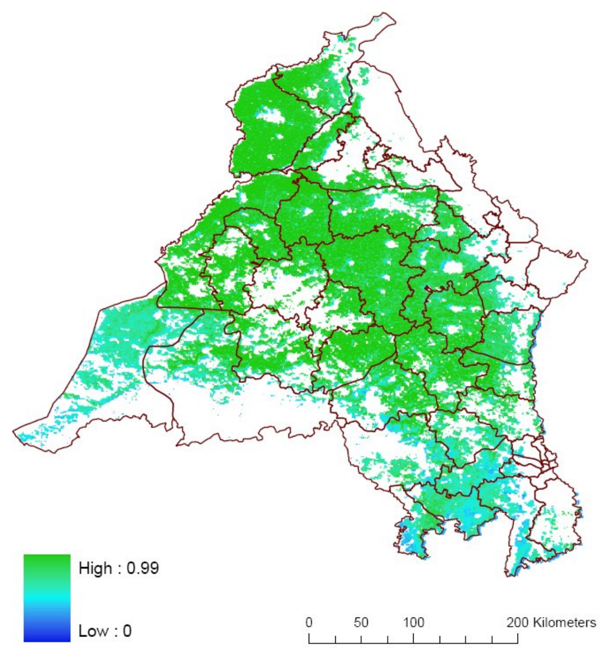

Figure 9. Vegetation Health Index map composited from leaf area index, chlorophyll content and equivalent moisture thickness of wheat.

Vegetation health index was developed using the equation described (Figure 9). Vegetation health index is unit less ranging from 0 to 1. Based on the VHI, study region was divided into four zones corresponding to four growth conditions of wheat crop (Table 3). Wheat area with very poor growth conditions were having VHI ranging from 0 - 0.25 and 0.26 - 0.50 for poor growth, 0.51 to 0.75 to good and above 0.75 for very good conditions (Figure 10).

Table 3. Four groups of vegetation growth condition based on vegetation health index.

Vegetation Health Index	Vegetation growth condition
0 – 0.25	Very poor
0.26 – 0.50	Poor
0.51 – 0.75	Good
0.76 – 1.0	Very good

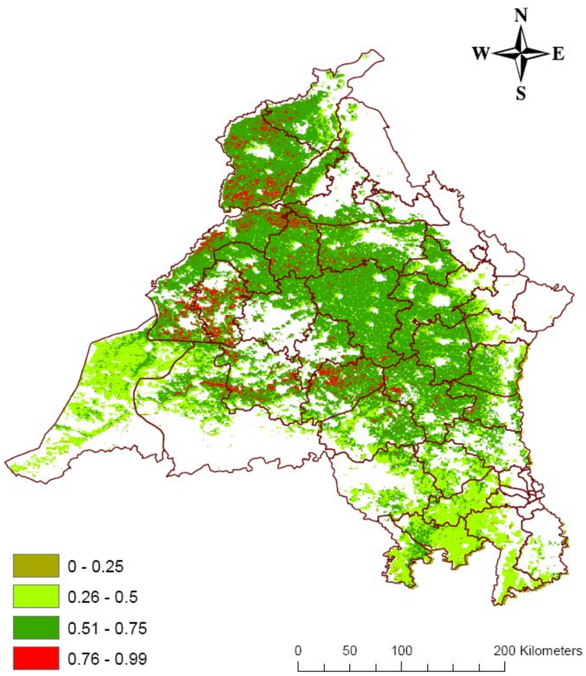

Figure 10. Zonation based on vegetation health index developed by combing chlorophyll content, Leaf area index and equivalent water thickness.

Conclusions

Crop growth monitoring at regional scale is very crucial for policy decisions. In the present study NDVI, RI and NDWI were proved to give reliable accuracy in retrieving these parameters. Vegetation health index thus developed can be used for site specific crop management for better utilization of available resources and maximizing the crop yield. This study has demonstrated the benefits of mapping the green leaf area index, total chlorophyll content and vegetation water content using Terra MODIS reflectance data. Using this technique other plant biophysical variables may also be retrieved for land cover classes characterized by contrasting canopy architectures, leaf inclination angles, and leaf biochemical constituents. The biophysical retrieval scheme used in this study is suitable for large-scale operations because the vegetation indices reflect differences in internal and external factors caused by plant species diversity, variable environmental and background conditions, and view and illumination geometry differences. The flexibility of this approach allows for easy implementation and evaluation for other environments and vegetation species compositions. Further, the use of directional satellite data, acquired from multi-angle sensors like the Multi-angle Imaging Spectro Radiometer (MISR) or from multi-temporal acquisitions from sensors with a wide range in viewing angles, in addition to extra wavebands located in the mid-infrared spectrum could probably enhance the retrieval accuracy of plant biophysical variables.

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References

Arnon, D. I. 1949. Copper enzyme in isolated chloroplast. Polyphenol oxidase in *Beta vulgaris*, Plant Physiol. 24:1-15.

Brown, L., J. M. Chen, S. G. Leblanc and J. Cihlar. 2000. A shortwave infrared modification to the simple ratio for LAI retrieval in boreal forests: an image and model analysis. Remote Sens. Env. 71:16–25.

Ceccato, P., N. Gobron, S. Flasse, B. Pinty and S. Tarantola. 2002a. Designing a spectral index to estimate vegetation water content fromremote sensing data: Part 1. Theoretical approach. Remote Sens. Env. 82:188–197.

Ceccato, P., S. Flasse and J. Gregoire. 2002b. Designing a spectral index to estimate vegetation water content from remote sensing data: Part 2. Validation and applications. Remote Sens. Env. 82:198–207.

Chen Jing M., M. Rich Paul, T. Gower Stith, M. N. John and P. Steven. 1997. Leaf area index measurements of boreal forests. J. Geophys. Res. 102(d24):29429-29443.

Chen, J. M. and J. Cihlar. 1996. Retrieving leaf area index for boreal conifer forests using Landsat TM images. Remote Sens. Env. 55:153−162.

Cohen W. B. and S. N. Goward. 2004. Landsat's role in ecological applications of remotesensing. Biosci. 54:535–545.

Cohen W. B., T. K. Maiersperger, Z. Yang, S. T. Gower, D. P. Turner, W. D. Ritts, M.

Berterretche and S. W. Running. 2003. Comparisons of land cover and L AI estimates derived from ETM+ and MODIS for four sites in north America: A quality assessment of 2000/2001 provisional MODIS products Remote Sens. Env. 88:233–255.

Gao, B. C. 1996. NDWI—a normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sens. Env. 58:257–266.

Gitelson, A. and M. N. Merzlyak. 1994a. Spectral reflectance changes associated with autumn senescence of *Aesculus hippocastanum* L. and *Acer platanoides* L., leaves. Spectral features and relation to chlorophyll estimation J. Plant Physiol. 143:286-292.

Gitelson, A. and M. N. Merzlyak. 1994b. Quantitative estimation of chlorophyll-a using reflectance spectra: Experiments with autumn chestnut and maple leaves. J. Photochem. Photobiol. (Biol.) 22:247-252.

Gitelson, A. and M. N. Merzlyak. 1996. Signature analysis of leaf reflectance spectra: algorithm development for remote sensing of chlorophyll. J. Plant Physiol. 148:494-500.

Gower, S. T. and J. M. Norman. 1991. Rapid estimation of leaf area index for forests using LICOR LAI-2000. Ecology 72:1896-1900.

Gower, S. T., C. J. Kucharik and J. M. Norman. 1999. Direct and indirect estimation of leaf area index, fapar, and net primary production of terrestrial ecosystems. Remote Sens. Env. 70:29–51.

Houborg, R., S. Henrik and B. Eva. 2007. Combining vegetation index and model inversion methods for the extraction of key vegetation biophysical parameters using Terra and Aqua MODIS reflectance data. Remote Sens. Env. 106:39–58.

Houborg, R. and B. Eva. 2008. Mapping leaf chlorophyll and leaf area index using inverse and forward canopy reflectance modeling and SPOT reflectance data. Remote Sens. Env. 112:186–202.

Hui F., T. Qingjiu and J. Zhenyu. 2003. Research and quantitative analysis of the correlation between vegetation index and leaf area index. Remote Sens. Inf. (2):10-13.

Lichtenthaler, H. K., A. A. Gitelson and M. Lang. 1996. Nondestructive determination of chlorophyll content of leaves of a green and an aurea mutant of tobacco by reflectance measurements. J. Plant Physiol. 148:483– 493.

Pyne, S. J., P. L. Andrews and R. D. Laven. 1996. Introduction to wildland fire. 2nd Ed., Wiley, New York.

Tripathi R., N. S. Rabi, K. S. Vinay, R. K. Tomar, C. Debashish and S. Nagarajan. 2012. Inversion of PROSAIL model for retrieval of plant biophysical parameters. J. Indian Soc. Remote Sens. 40(1):19–28.

Turner, D., W. Cohen, R. Kennedy, K. Fassnacht and J. Briggs. 1999. Relationships between leafareaindex and Landsat TM spectral vegetationindices across three temperate zone sites. Remote Sens. Env. 70:2–68.

Vermote, E. F. and A. Vermeulen. 1999. Atmospheric correction algorithm: Spectral reflectances (MOD09). Algorithm Theoretical Background Document available online at http://modarch.gsfc.nasa.gov/data/ATBD/atbd_mod08.pdf

Zlatev, Z. and F. J. Lidon. 2012. An overview on drought induced changes in plant growth, water relations and photosynthesis. Emir. J. Food Agric. 24(1):57-72.