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Monitoring Directional Dynamics of Growing Wheat Crop Canopy Using Ground based Time Series Remote Sensing Radiative Measurements

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Abstract

Agricultural crop monitoring is an issue of extreme importance under global climate change, increased natural disasters and population explosion threatening global food security. In this paper, dynamic behaviour of spectro-directional reflectance properties of wheat canopy has been studied using radiometric measurements performed over a wheat field during the entire crop life cycle under varying viewing geometries. The study reveals that biological growth rhythm of wheat crop associated with continuous alteration in canopy condition particularly in terms of optical and morphological properties during the life cycle results in a distinct and systematic changing pattern of bidirectional responses in red and near Infrared (NIR). Analysis shows appreciable sensitivity of radiometric measurements both in the red and NIR regions to crop phenological transformation and changes. Soil background influenced the overall angular anisotropy pattern and manifested relatively high surface reflectance specifically at the early growth stage. At this stage, changes in viewing direction give rise to additional variability in directional reflectance due to varying proportion of soil-vegetation and enhanced contrast between wheat crop and its soil background. Both amplitude and angular pattern of directional response of the canopy undergo appreciable changes with time. Asymmetry in directional reflectance has been noticed in both the spectral regions on either side of nadir in the principal plane. In this connection, time varying angular characteristics of normalized difference vegetation index (NDVI) has also been studied in relation to crop growth.

Keywords: Bidirectional reflectance, NDVI, Temporal pattern, Chlorophyll, Remote sensing.

Introduction

Monitoring of terrestrial vegetation and agricultural crops is one of the major objectives in remote sensing. Proper use of remote sensing technology can provide valuable information on the growth and condition of agricultural crops. A series of studies dealt with the monitoring of the condition of vegetation and agricultural crops using remote sensing (Dhar et al. 2021; Mehda et al., 2021; Morgan et al. 2021; Panchal et al., 2021; Refat et al. 2020; Esetlili et al., 2018; Gallo *et al.*, 1985; Rahman, 2001; Sellers, 1985). The absorption and reflection characteristics of solar radiation from plant canopies show distinct variation between different crops depending on the leaf architectural and optical properties as well as on the properties of underlying surfaces. During the life cycle of an agricultural crop, the architectural and optical properties (*e.g.*, leaf area, vegetation height, vegetation cover, absorption, scattering of individual leaf elements *etc.*) change (Tucker and Sellers, 1986) and follow a definite rhythm for each crop type. As a result, crops interact differently at each stage of its life cycle with the incident solar radiation and results in distinct variation in directional response. Multi-temporal remote sensing measurements over a surface covering a wide range of viewing and illumination angles provide the directional response dynamics that resulted in from the architectural and phenological changes within a canopy. This variation in directional response characteristics can be used for acquiring relevant information on the crop condition (Widlowski et al., 2001; Rahman 1996). The effective use of these characteristics requires a thorough understanding of the radiative transfer through vegetation canopy in relation to their morphological and optical properties as well as the perturbations of solar radiation during its traverse through the atmosphere.

Various space based remote sensing sensors such as the Multi-Angle Imaging Spectro Radiometer (MISR) (Diner et al., 1998; Diner, 1998; Pagano and Reilly, 1989) or the POLarization and Directionality of the Earth's Reflectance (POLDER) (Deschamps et al. 1994) or the Along-Track Scanning Radiometer (ATSR-2) (Stricker et al., 1995) are presently operational specifically for multiangular observation of the earth's surface and its atmosphere. The growing concern due to the development of a number of diversified space-based sensors has resulted in a series of research works the world over (Pinty et al., 2001, 1990; Widlowski et al., 2001) and created new opportunities to conduct global and regional scale investigation of terrestrial surface (Gobron et al., 2000). New techniques and algorithms are required to fully utilize the immense potentialities of such space-based technology.

As part of continual effort, spectral index-based approaches (e.g., Jaskula et al. 2019; Ruiz et al., 2019; Gobron et al., 2000; Gobron et al., 1999) or model based quantitative approaches (e.g., Ledezma et al. 2020; Diner et al., 1998; Martonchik et al., 1998; Moriyal et al., 2018; Widlowski et al., 2001; Rahman et al., 1993a, 1993b etc.) have been made by various authors to extract information from such radiative measurements. Owing to the fact that multiangular measurements are influenced by the spatial heterogeneity of the surface, one can yield statistical information about the type of surface heterogeneity through appropriate characterization of anisotropic effect (Widlowski et al., 2001). Ground-based radiometric measurements of vegetation reflectance are often conducted to supplement and enrich the understanding of various biospheric processes occurring in a geographic area and their possible linkages with the radiative measurements. Near-surface radiometric observation over the entire growth cycle of a crop provides comprehensive knowledge on the pattern and processes of the dynamic changes in spectral reflectance characteristics due to crop growth mechanisms (Deering and Eck, 1987; program like Assimilation of Multisensor & Multitemporal Remote Sensing Data to Monitor Vegetation and Soil Functioning, of which the acronym is ReSeDA (Remote Sensing Data Assimilation) operated by several European institutes and companies or program like HAPEX-Sahel (Hydrological and Atmospheric Pilot Experiment in the Sahel).

Remarkable progresses have been achieved during the last few years in directional remote sensing. Specifically, the integrated use of field goniometers and directional measurement setups to validate airborne or space-borne directional data has become very popular since the late 1990 (e.g., Chopping et al., 2003; Huete et al., 2002). Directional ground measurements have become of crucial importance for validation of air and space borne sensors as well as the derived products.

The aim of this work is to study the dynamic behavior of directional response characteristics of wheat crop during different growing stages covering early to near harvesting periods in view of monitoring the growth and condition of wheat crop using multitemporal directional remote sensing data.

Interaction of Solar Radiation and Plant Growth

A vegetation canopy composed of components like leave, stems, flowers etc. can be considered as an ensemble of scattering elements, bounded by the background soil. Radiation incident on the surface is scattered by different canopy components and a part of this scattered radiation leaves the canopy in the upward direction (Bunnik, 1978). Such plant-canopy interaction largely regulates the growth and development of plants by maintaining numerous biological processes within the canopy through thermal effects, photosynthetic effects, and photomorphogenic effects of radiation (Vogelmann and Bjorn, 1986; Kumar et al., 2001). Major portion of the incoming solar radiation (above 70 percent) absorbed by plants is converted into heat and is used for maintaining plant temperature and for transpiration (thermal effects) (Slatyer, 1967; Gates, 1965). About, 28% of the absorbed incoming solar energy in the photosynthetically active region is utilized by the plant canopy for photosynthetic activities that ultimately produce the carbohydrates. Incident solar radiation interacts with the plant canopy either through reflection, absorption or transmission. Radiation and interception characteristics of a green vegetation canopy is determined principally by the wavelength of radiation, angle of incidence, surface roughness and optical properties of the canopy components, biochemical contents of the leaves, leaf thickness, leaf structure, leaf angle distribution (LAD), chlorophyll and carotenoid content of leaves, distribution of yellow foliage etc. (Guo et al., 2021; Ross, 1981; Bunnik, 1978; Choudhury, 1987).

A plant-canopy system undergoes to systematic changes during the life cycle following the biological growth rhythm. Life cycle of a plant generally consists of

i. Planting stage,
ii. Development and Growth stage,
iii. Flowering stage, and
iv. Maturing and Harvesting stage.

In the early stage, green vegetation has high chlorophyll content that causes high photosynthetic action in presence of leaf water and photosynthetic radiation producing more carbohydrate that enhances the plant growth. With the passage of time both leaf water and chlorophyll content decrease as leaf dries up resulting in reduced photosynthetic activity.

In the photosynthetic activity, chloroplasts absorb light energy and CO_2 and H_2O are combined with absorption of energy in the photosynthetic region to produce the carbohydrate that maintains the growth and development of a plant canopy (Kumar et al., 2001). In such a process, absorption of radiation in the photosynthetic region as conditioned by the chlorophyll of green leaf is a prime factor that controls the production of carbohydrate i.e., growth of the plant. The presence of water in individual leaf is also an important criterion. Eventually, the absorbed energy in the photosynthetic region over the life cycle of a plant canopy is related to the growth of the crop and to a greater extent to crop yield.

$$CO_2 + H_2O \xrightarrow{sunlight} CH_2O + O_2 \qquad (1)$$

In a plant canopy, the cellular structure and composition of the leaves as well as the presence of photosynthetically active pigments principally determine the variation in absorption and reflectance characteristics. The cells in plants act as very effective scatterer of light because of the high contrast in the index of refraction between the water-rich cell contents and the intercellular air spaces. However, due to the presence of light absorbing pigments (chlorophylls and carotenoids) in plants, vegetation has relatively low reflectance in the red region of the solar spectrum (Hall and Rao, 1987). Among all light absorbing pigments in vegetation, chlorophyll tend to dominate the spectral response as there is 5 to 10 times as much chlorophyll as carotenoid pigments. In general, light is scattered by refraction and scattering (both Rayleigh and Mie) as it enters the plant leaf. The distribution of air spaces and the arrangement, size and shape of cells influence the passage of light in the leaves. Dynamic changes occur in the radiative transfer properties of vegetation particularly in terms of its absorption and scattering during different growth phases. Chlorophyll activity decreases and leave become yellowish.

Experimental Approach

In the visible region of the solar spectrum, absorption is maximum for green vegetation due to chlorophyll activity and in the near-infrared high scattering of incident solar radiation is caused by leaf scattering mechanisms. Consequently, proper combination of the data acquired in the two spectral regions provides valuable information on vegetation condition. One of the most widely used combinations is the normalized difference vegetation index (NDVI) (Choudhury, 1987; Sellers, 1987; Dickinson, 1983) as given below,

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \qquad (2)$$

where, ρ_1 and ρ_2 are the reflectances in the visible and near-infrared respectively. Such combinations result in enhanced contrast between vegetation and other surface classes.

Measurements of Directional Reflectance

In the present study, directional reflectance measurements were carried out over wheat canopy during different stages of wheat growth particularly on the 15th and 31st January, 7th and 17th February and 11th and 21st March 2005. These dates correspond to early stage, middle stage and senescent stage respectively of wheat canopy. An Exotech Radiometer, Model 100 AX with four of its channels positioned between 0.45-0.52 μm, 0.52-0.60 μm, 0.63-0.69 μm and 0.76-0.90 μm has been used for the measurements. The radiometer was placed about 130 cm above the ground surface.

In general, collection of bidirectional reflectance data often involves observation of the canopy in numerous nadir and azimuth directions (e.g., Ranson et al., 1984; Leblanc et al., 2001 and Coca et al., 2001). For a wide range of canopies (those both horizontally and azimuthally isotopic, for example), radiometric measurements indicate that both the "hot spot" and the "dark spot" (local maximum and minimum, respectively, in the bidirectional reflectance) are found in view directions in the principal plane (Kriebal, 1978; Khlopenkov et al., 2004; Ranson et al., 1985; Goel and Deering, 1985). Goel (1987) reported that bidirectional reflectance as a function of the view zenith angle in the solar plane (principal plane) has three informative regions for remote sensing: (i) the region around the hot spot where shape of the canopy bidirectional reflectance is influenced by the leaf dimension; (ii) the region around the nadir direction where the shape of the canopy bidirectional reflectance is influenced by the soil reflectance and in individual plant geometry; and (iii) the region near the view angle of pi/4 on the opposite side of the sun which is influenced by the optical properties of the leaves and leaf area index. As such for certain applications, it is possible to restrict observations to view directions preferably in the principal plane rather than all possible directions across the hemisphere (e.g., Weiss et al., 2000; Galvao et al., 2004). Eventually, the geometric ranges of radiometric measurements for the present study were kept limited to principal plane only. Such an operation allows us to keep a limited size of the data set and thereby significantly reduced the time required to collect it while keeping the major ranges of variation in the canopy bidirectional reflectance. Measurements were carried out in the principal plane from an angle of 60° in the backward direction to 60° in the forward scattering direction by a step of 10°. Viewing zenith angle was kept limited within 60° because beyond that limit specular reflection largely dominates involving interaction with mostly top surface layer of the canopy (Grant, 1987) without significant penetration through inside the canopy. Radiometric measurements performed from such high viewing angles often suffer from significant contaminations due to large atmospheric path particularly from satellite platform (which is our prime concern) (Rahman, 1996). Measurements were performed from approximately the same location on different dates that ensures the multi-date measurements of approximately the same canopy elements.

Table 1. Information on solar angle and crop height

Date	Solar zenith angle	Vegetation height (cm)
December 18, 1994	43°	--
January 15, 2005	48°	24.7
January 31, 2005	46°	44.5
February 07, 2005	44°	56.2
February 17, 2005	47°	85.9
March 11, 2005	37°	87.4
March 21, 2005	38°	88.2

The solar zenith angle corresponding to each measurement was noted and is given in table 1. The sky was almost cloud free with a medium range visibility. Upwelling radiance of a BaSO4 panel was measured at each sampling station, before and just after measurements of wheat reflectance, and used as reference (Daughtry et al., 1982). Radiometric data were collected close to solar noon (between 11 a.m. and 1 p.m.); so, changes in solar zenith were minimal. Each measurement campaign took about half an hour. Figure 1 shows the photographs of non-irrigated wheat field at different growth stages on different dates, (a) 31st

January, (b) 17th February, (c) 11th March and (d) 21st March covering from early to near harvesting stages. In the present study, we have used only the data acquired in the 0.63-0.69 μm (strong chlorophyll absorption) and 0.76-0.90 μm (high scattering by leaf) two characteristically important areas representative of the red and NIR regions of the solar spectrum respectively.

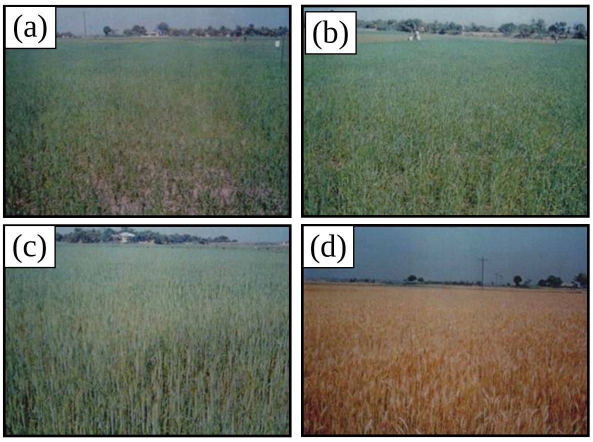

Fig. 1. Photographs of wheat field at different growth stages on different dates, (a) 31st January, (b) 17th February, (c) 11th March and (d) 21st March covering from early to near harvesting stages.

Preprocessing of Data

Since the radiometric measurements have been performed in the field, atmospheric diffuse radiation significantly contributes to the total illumination of the canopy depending on the illumination geometry and atmospheric condition. This results in a partial smoothing of the bidirectional reflectance field, and we have taken into account by expressing the measured reflectance ρ_m $(\theta_1 \theta_{2,} \phi)$ as a function of actual surface reflectance $\rho(\theta_1 \theta_{2,} \phi)$ as follows (Rahman *et al.*, 1993b):

$$\rho(\theta_{1,}\theta_{2,}\emptyset) = \rho_m(\theta_{1,}\theta_{2,}\emptyset) + [\Re(\theta_{1,}\theta_{2,}\emptyset) - \rho_m(\theta_{1,}\theta_{2,}\emptyset)]\, f_d(\theta_1) \quad (3)$$

where, θ_1 and θ_2 are the solar and viewing zenith angles respectively and ϕ is the relative azimuth angle between solar and viewing direction. The term $\Re(\theta_1 \theta_{2,} \phi)$ is the angular average of the directional reflectance and it can be estimated by the following equation (Tanré *et al.* 1983):

$$\Re(\theta_{1,}\theta_{2,}\emptyset) = a\, \rho_m(\theta_{1,}\theta_{2,}\emptyset) + b \quad (4)$$

For a given atmospheric condition, *a* and *b* are two spectral band dependent coefficients.

In equation 3, atmospheric function f_d (θ_1) is the ratio of the diffuse and total transmittance of the atmosphere on the incoming direction for the combined direct and diffuse solar radiation and is given by,

$$f_d(\theta_1) = \frac{t(\theta_1)}{T(\theta_1)} \quad (5)$$

$T(\theta_1)$ and $t(\theta_1)$ are the diffuse and total (direct and diffuse) transmittance of the atmosphere due to combined aerosol and molecular scattering for the incoming solar radiation.

In the equation atmospheric function f_d (θ_1) is the contribution due to the diffuse radiance that modifies the bidirectional signature of the direct beam. For an atmosphere without scattering f_d=0 and the observed bidirectional reflectance equals the bidirectional reflectance for direct radiation ρ_s; when f_d=1, which happens when illumination does not include any direct component (e.g., complete overcast), the reflectance of the surface equals average directional reflectance $\Re(\theta_1, \theta_{2,} \phi)$; whereas for an atmosphere with moderate optical thickness, f_d has some intermediate value which smoothes the bidirectional contribution of the direct beam.

Table 2. Optical properties of wheat crop (Bunnik, 1978; Choudhury, 1987)

Wave length (λ)	Leaf reflectance (ρ)	Leaf transmittance (τ)	Leaf absorptance (α)
0.670	0.075	0.007	0.918
0.870	0.520	0.440	0.040

All radiometric measurements have been preprocessed by using equation 3 to 5. Simple atmospheric functions of SMAC (Simplified Method for Atmospheric Correction) (Rahman and Dedieu, 1994) have been used to calculate the diffuse and total transmittance of the atmosphere on the incoming direction for the combined direct and diffuse solar radiation $t(\theta_1)$ and $T(\theta_1)$ respectively (equations 3-5) for the spectral bands in which radiometric measurements were performed. An average aerosol loading of 0.15 is considered for the atmospheric correction and data have been corrected both for Rayleigh and aerosol scattering. An average continental model of aerosol has been considered for atmospheric correction of data.

Results and Discussion

Wheat crop field under the present study was located in the Narayanganj district in Bangladesh. The crop was planted on the 20th December 1994 and was non-irrigated throughout the crop cycle. An average leaf inclination of wheat leave was found to be about 45° to 62° which is close to that mentioned by Choudhury (1987) and wheat has an erectophile leaf angle distribution (Choudhury, 1987). While an average of 260 to 320 plants was counted per square meter. Each plant contained an average of 6 leaves. Figure 2 shows a plot of crop height as a function of days after planting. It is evident that crop height increased up to 17 February and attained a height of about 86 cm. Apart from that date crop height became almost unchanged.

During the life cycle of a crop canopy, various changes generally occur in the properties of the canopy (Hatfield et al., 1984; Tucker and Sellers, 1986). The dynamics of the bidirectional reflectance of a given vegetation canopy are generally controlled by the canopy geometry, optical properties of canopy elements (e.g., leaves, branches, stems, dead vegetation, soil etc.) and sun zenith angle (Kimes, 1983; Sandmeier et al., 1998). The role of solar and viewing zenith angles as well as leaf orientation angle is very much important in determining

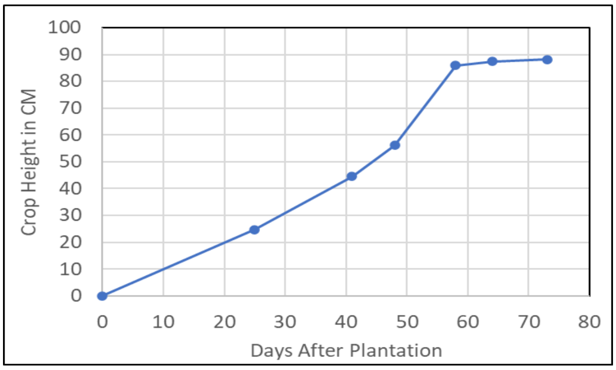

Fig. 2. Crop height as a function days after planting. Measurements were performed over a wheat crop area situated in the Narayanganj district in Bangladesh from January to March 2005.

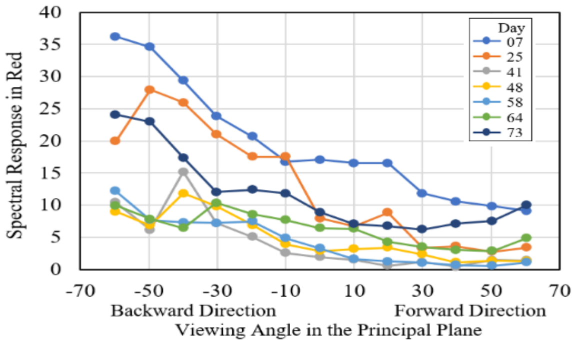

Fig. 3a: Directional reflectance in the red spectral region (0.63-0.69 µm) for a wheat canopy as a function of viewing angle in the principal plane on different dates, 15th January, 31st January, 7th February, 17th February, 11th March and 21st March covering from early to near harvesting stages. The solar zenith angles correspond to 48°, 46°, 44°, 47°, 37° and 38° respectively.

the directional response of a given vegetation canopy (Ranson et al., 1986; Rahman et al., 1999). On the other hand, the optical properties of the vegetation determine the wavelength dependent nature of the anisotropy reflectance (Tucker and Sellers, 1986).

Temporal Dynamics of Wheat Radiative Responses

Directional Reflectance in the Red

Figure 3a shows the plot of measured directional reflectance in the red spectral region as a function of viewing angle in the principal plane for the wheat crop at different growth stages covering, early, middle and senescent phases. The sun zenith angle corresponding to different dates are given in table 1 and table 2 provides values of important optical parameters for wheat crop. From these figures it is evident that directional reflectance of wheat canopy shows significant variability between different growth stages and over the viewing angles considered. In the red wavelength, overall canopy reflectance is relatively small due to high chlorophyll absorption of solar radiation by the green vegetation. In all the dates, bidirectional reflectance of wheat canopy is relatively high in the backward scatter direction and decreases from around 30°- 40° in the backward scattering direction towards forward scattering directions. Variations are maximal in the backward scattering direction. An almost linear behaviour of bidirectional reflectance (minimum variation) is observed apart from nadir towards forward scattering direction up to 60° except for March 11 and March 21. A slight increase in reflectance is observed after 50° and 30° in the forward scattering direction on March 11 and March 21 respectively. The lowest value of the bidirectional reflectance is observed for an angle of about 20°- 30° in the forward scattering direction.

The observed angular variability in directional reflectance is governed by a number of physical mechanisms and factors (Moriya1 et al. 2018; Kimes, 1983; Ranson et al., 1986; Rahman et al., 1999; Sandmeier et al., 1998). A maturing wheat canopy for instance can be considered as first layer containing ears and stalks, a second layer with green leaves and a third layer bounded by senescent leaves and soil (Bunnik, 1978). Each of these canopy elements has different spectral response properties. As such variation of observation geometry induces varying proportion of influences of these canopy components on the measured reflectance value.

Vegetation components at the top of the canopy receive greater irradiance and hence scatter a larger amount of solar flux towards the sensor than the components at the bottom of the canopy (Deering and Eck, 1987). The gap effect is produced when off-nadir view angle and the proportion of well-illuminated upper canopy component viewed from the sensor's field of view increases. Obviously, this effect is clearly related to the vertical structure of the canopy and the spatial distribution of elements that determine the fraction of soil, vegetation and shadows in the scene for a specific sun zenith angle. Back-shadow effect is related to the orientation of the canopy components and the irradiation condition derived from the shadow's pattern.

In the principal plane the combination of both, gap and back-shadow effects produce a wide variation of directional reflectance with useful information about canopy structure (Leblanc et al., 2001) and LAI (Camacho et al. 2001). The solar zenith angle jointly with the leaf orientation angle determines the effective intercepting area that is used for radiation incidence. For a normal incidence of radiation (normal to the leaf plane), maximum radiation is intercepted by the leaf, whereas, away from the normal decreases the amount of intercepted radiation. At the same time, for a normal incidence (normal to the surface) maximum radiation interacts with the background soil and away from the normal decreases the interaction with soil and increases interaction with vegetation. This effect is very strong in the soils due to the fact that the single scattering governs the dispersion of radiation. Furthermore, for a given canopy, viewing angle determines the amount of soil that is exposed to solar radiation in that direction. As the viewing angles move from nadir, less soil and more vegetation are seen.

In the red spectral region chlorophyll absorbs heavily and the reflected radiation travels a shorter optical pathway with a reduced probability of internal multiple scattering than with leaf transmission or at wavelengths with a low absorptance (Bunnik, 1978). Vertical structure, relatively higher sun zenith angle (about 37°-48° for the measurements on different dates) with very high absorptance (about 0.918) produce very dark shadows in the forward scattering direction and thus increases the contrast between the illuminated and shadowed areas. Lower canopy layer receives less irradiation and reflects less than the upper canopy layer. Consequently, the differences between the upper and the lower layers in the forward scattering are negligible, reducing the gap effect.

In the figure, asymmetry in bidirectional reflectance value in the red spectral region is clearly demonstrated along the principal plane on either side of nadir. In the forward scatter direction large shaded areas are seen resulting in a decreasing reflectance, whilst in the backscatter hemisphere the sunlit areas are predominant and thus the reflectance is enhanced. Such an asymmetry in canopy reflectance arises mostly due to non-horizontal leaves. Particularly, the erectophile leaf angle distribution (non-horizontal) of wheat canopy favors the gap effect and thereby, increases the anisotropy. This is generally manifested as an increase of reflectance when the off-nadir viewing angle increase for the solar zenith angle considered. This is in conformity with the observation made by various authors (e.g., Holben et al., 1986; Deering and Eck, 1987 etc.).

The measured canopy bidirectional reflectance is basically composed of diffuse and specular components (Grant, 1987). Both diffuse and specular reflectances are dependent on the physical and chemical structure of the leaf, geometry of the internal structure and of the leaf surface being the primary factor influencing differences in reflectance among leaves. At wavelengths where absorption by plant tissue is high, the bidirectional reflectance mostly comprises of polarized light. When absorption is low, diffuse non-polarized reflectance from the internal structure of the leaf predominates. Thus, at photosynthetically active regions of the spectrum, the principal factor in reflectance is the polarized reflectance from the leaf surface. Overall reflectance increased with increasing viewing angles. Diffuse reflectance varied little with changing angles, while polarized reflectance does, thus the changes in total reflectance as a function of angle describes the changes in surface reflectance. For a moderate solar angle (30°-40°), the degree of polarization increases with viewing angles and is maximal around or above 40°-50°.

A sharp rise in reflectance is observed at about 40°-50° in the backward direction, the angle closely corresponds to solar zenith angle at that time. In this case, increase in reflectance amplitude of about 158 percent in comparison to nadir values is noticed. The sharp rise in reflectance was due to the hot spot *i.e.*, a condition when a surface is observed from the same direction as that of illumination. For that particular observation-illumination geometry, less areas under mutual shadowing of the leaf elements and more illuminated layers of the canopy are seen (Rahman *et al.*, 1999). The width and intensity of the hot spot is closely related to the structural properties

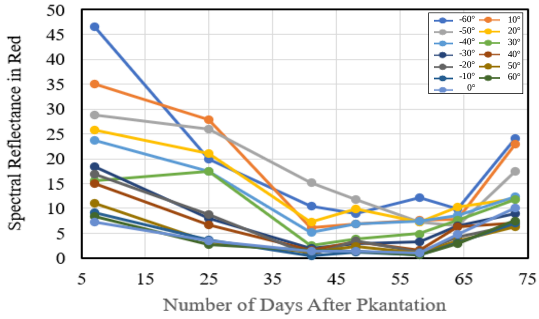

Fig. 3b: Directional reflectance in the red spectral region (0.63-0.69 μm) for the wheat canopy as a function of number of days as mentioned earlier after plantation covering from early to near harvesting stages for different viewing angle in the principal plane.

of the crop canopy. On either side of the hot spot region *i.e.*, towards forward scatter direction and for higher viewing angles in the backward scatter direction reflectance decreases. Hot spot is generally interpreted as a coherent transmission into the canopy (Breon et al., 2001), providing information of the ratio between horizontal (leaf scale) and vertical scales (canopy scale) of the canopy.

Figure 3b shows the variation of directional reflectance in the red spectral region as a function of different dates

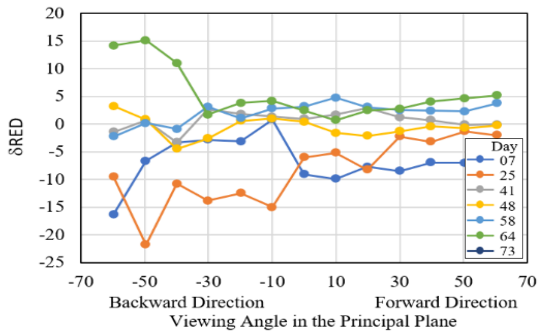

Fig. 3c: Changes in measured bidirectional reflectance ($\delta\rho_{red}$) of wheat crop in the red wavelength (0.63-0.69 μm) as a function of number of days after plantation covering from early to near harvesting stages for different viewing angle in the principal plane. For a given date, change in red reflectance $\delta\rho_{red}$ has been calculated by subtracting the red reflectance value on the immediate earlier date from the reflectance value on the date considered.

while figure 3c shows the changes in red reflectance ($\delta\rho_{red}$) between consecutive measurement dates as a function of different dates covering the life cycle of wheat crop under the present study for different viewing angles. For a given date, changes in red reflectance $\delta\rho_{red}$ has been calculated by subtracting the reflectance value on the immediate earlier date from the reflectance value on the date considered. This figure depicts that temporal pattern of bidirectional reflectance in the red spectral region shows a "hill shape" pattern. Moreover, sensitivity of temporal reflectance pattern to vegetation growth shows a significant dependency on the angle of observation.

Contrast is high towards large viewing angles in the backward scattering direction. Minimum sensitivity is noticed in the forward scattering direction particularly for the large viewing angle. For the red reflectance, significant changes are noticed for the 1st 50 days after plantation and then a relatively stable and finally near the end of the crop life cycle a noticeable change occurred. However, near the middle stage of the crop, red reflectance shows minimum changes with respect to earlier measurements.

Comparison of directional patterns of measured reflectance on different dates exhibits a systematic variation due to crop phenological development and growth. Changes in canopy structure and pigments throughout the developmental stages of the wheat canopy were translated into changes in the spectral signature. Referring to the reflectance curve of 15th January (Figure 3a) corresponding to the early growth stage of the crop (an incomplete canopy), amplitude of reflectance as well as its angular variation in the red wavelength is relatively higher as compared to the reflectance value in the other stages of growth. This is due to the fact that at this stage vegetation cover and leaf area were very much small and maximum soil background was exposed to incident solar radiation. Relatively large scattering from background soil due to agronomic factor particularly the non-irrigated field condition resulted in relatively high soil reflectance that enhanced the incomplete canopy signature. Soil influences on canopy reflectance have been reported in various issues (e.g., Daughtry et al., 1980; Fernandez et al., 1994; Huete et al., 1985). Highest value of reflectance was observed over the viewing angles in the backward scattering direction typically about 0.285 for a viewing angle of 50°. Angular variation of reflectance value for larger viewing angles in the forward scattering direction was relatively small. Reflectance value at nadir was about 0.14 for the same crop area under bare soil condition (just before plantation) and while a decrease of about 43.3% is noticed on the 15th January with respect to bare soil condition.

Referring to the situation on January 31 (figure 3a), the crop was in its growth phase (tillering stage) and was not well developed. Eventually, the soil contribution to canopy reflectance was still large. Although the spectral signature showed some characteristic features of green vegetation (lower reflectance in the red region), the average reflectance in the red spectral region was relatively high. Young immature leaves have a compact mesophyll; as leaves mature, air spaces in the mesophyll increase as cells are pulled apart or cells deteriorate. Leaf reflectance in the red portion of the spectrum changes with maturation (Sinclair at al. 1971). Since soil reflectance was higher than the leaf reflectance, bidirectional canopy reflectance decreased as LAI increased.

However, with the passage of time, increased vegetation cover and leaf density resulted in increased photosynthetic activity in this spectral region. Near the middle stage as on the 7th February, the vegetation was fully grown up and chlorophyll activity became maximal. Consequently, major portion of the incident solar radiation was absorbed by the vegetation in the photosynthetic region. Thus, reflectance attained its minimum value as on the 31st January, about 0.02. Afterward, reflectance attained a value of about 0.033 on the 17th February, which was slightly higher than the previous measurement on the 7th February (about 0.029). During the observation on the 17th February, flowering of wheat was observed and the slight increase in reflectance value is probably due to this flowering effect. With the onset of crop flowering, leaf yellowing, and subsequent leaf wilting begins. At the initial stage, this process affects the leaves near the ground, but as crop senescence progress more and more leaves are affected. Following the phenological sequence, the crop became yellowish green on the 11th March and became ripe and nearly dry on the 21st March.

Bidirectional reflectance measured on February 17, March 11 and March 21 shows progressive increase of reflectance. For the data acquired on the 11th and 21st March, increase in reflectance value is observed for increase in viewing angle near the larger viewing angle in the forward scattering direction. Towards higher viewing angle in the forward scattering direction, reflectance has an increasing trend particularly near the middle stage. Non-smooth variation is due to spatial heterogeneity of wheat area and exposed soil. Relatively smooth angular variation was observed on the plot of February 11 when canopy cover was maximum and overlapping. It is probably due to more homogeneous surface characteristics at that time.

At the initiation of senescence phase of the wheat canopy as on the 11th March, degradation of chlorophyll activity of crop resulted in an augmentation of reflectance value in the red spectral region. An increase of about 42 percent with respect to the minimum reflectance value (about 0.033 on the 31st January) is noticed for the wheat crop under present investigation. In fact, loss of absorbing chlorophyll leads to increasing reflectance as well as transmittance. Changes in leaf reflectance of green leaves with maturation and senescence are not only associated by degeneration of chlorophyll and yellowing, but the internal leaf mesophyll structure also undergoes to systematic modification. Canopy structure changes drastically as a consequence of shrinking of leaves. Eventually, a single cause does not always affect only one reflectance parameter instead multispectral responses are often interrelated in a complex manner (Bunnik, 1978).

During leaf senescence, relatively faster degradation of chlorophyll in comparison to carotenes results in significant reduction of absorption by chlorophyll in the red spectral region (Sanger, 1971). Carotenes and xanthophylls now become the dominant chemicals in leaves, and the leaves appear yellow because both carotene and xanthophyll absorb blue light and reflect green and red light. Yellow colour is originated as a result of combination of the green and red lights. As the leaf dies, brown pigments (tannins) appear and the leaf reflectance and transmittance over the 400nm to 750nm wavelength range decreases (Boyer *et al.*, 1988) and thus affects the canopy radiative transfer mechanisms.

Finally, at the near harvesting stage, most of the chlorophyll activity ceases and the leaf becomes relatively dry, this results in relatively high reflectance in the red about 0.10 on the 21st March. In the red region bidirectional reflectance measured on March 21 shows slight increase in reflectance as compared to that on March 11. The data of 21st March also exhibits relatively high reflectance but smaller than that of the 15th January due to decreasing vegetation activity and as a result reflectance value decreased as on the 15th January reflectance values of about 0.08 at nadir is noticed.

Crop growth sequences resulted in systematic variation in the value of directional reflectance. Eventually, temporal pattern of directional reflectance can be characterized by relatively high reflectance value at the early stage of the crop, then a gradual decrease in reflectance during the growing phase. Finally, reflectance increases gradually at the initiation of the senescent phase. Such a trend is a general feature for all the observational geometries under the present study. However, the degree of curvature as determined by the sequential variation of directional reflectance varies significantly over the viewing angle. Sensitivity of directional reflectance to crop growth sequences is strongly dependent on the observational geometry. Higher sensitivity is noticed for the larger viewing angles in the backward scattering direction. While, sensitivity decreases for observation towards forward scattering direction. Thereby, resulted in an increasingly flattened nature of the temporal bidirectional reflectance curve as we move from the backward scattering to forward scattering direction.

A noticeable difference in the angular pattern of bidirectional reflectance is observed between the early stage and senescent stage of the canopy. In the early stage, directional reflectance in the red spectral region exhibits an almost linear behaviour particularly over viewing angle of 30° and above in the forward scattering direction. Whereas in the middle stage or later on systematic rise of canopy reflectance is noticed, for viewing angle larger than 30° in the forward scattering direction. Moreover, in this spectral region, dynamic changes in canopy directional reflectance are noticed over the early part of the life cycle. No appreciable variation is observed in directional reflectance during the middle stage of the crop. Though certain changes have been noticed near the end-of-life cycle.

Directional Reflectance in the NIR

Figure 4a shows the variation of measured directional reflectance in the near-infrared (NIR) as a function of viewing angle in the principal plane for different dates ranging from the early to near harvesting stage. In this spectral region, wheat canopy reflectance is relatively high for all the viewing angles considered on different dates. Green plants generally have high reflectance and transmittance and very low absorption in the NIR region (Table 2) (Billings and Morris, 1951; Maas and Dunlap, 1989; Gausman, 1985). Involved scattering mechanism can be explained by the multiple reflection in the internal mesophyll structure, caused by the transition of refraction index between the cell walls and the intercellular air cavities (Bunnik, 1978; Sinclair *et al.*, 1971). Multiple scattering increases the magnitude of reflectance (Goel, 1987). Transmittance in all wavelengths approached Lambertian scattering. A

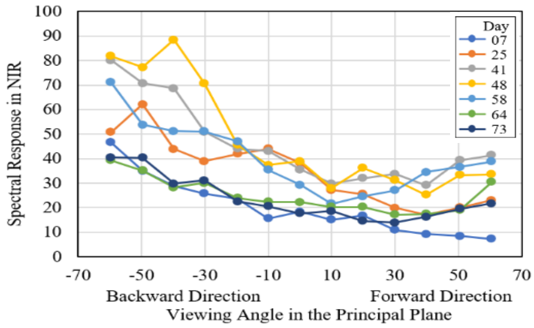

Fig. 4a: Same as in Figure 3a, except for the NIR spectral region (0.76-0.90 μm).

reflectance value of about 0.40 in the NIR at nadir is noticed on the 7th February whereas the corresponding value of reflectance is about 0.042 in the red on the same date. The shape of bidirectional reflectance curve in the NIR is similar to that in the red region that is consistent with the observation of Goel (1987).

A somewhat similar trend of reflectance is observed in NIR as compared to that in red region. Reflectance is maximum for an angle of 30°-40° in the backward scattering direction. For all the dates, directional reflectance gradually decreases from 40° in the backward scattering direction up to 40° in the forward scattering direction. Apart from 40° in the forward scattering direction slight increase in canopy reflectance is noticed. The mechanism of increased NIR reflectance for larger viewing angle in the forward scattering direction can be explained in terms of the directional scattering properties of both the soil and the vegetation components. In general, the scattering properties of the soil cause the maximum and minimum response to be in the extreme backscatter direction and forward scatter directions respectively. The effect of vegetation modifies this trend to some extent and is responsible for the increase in signal in the extreme forward scattering direction (Holben et al., 1986; Kimes 1983). In this spectral region, reflectance value changes significantly over the viewing angles considered. The gap effect causes the typical bowl-shape of the bidirectional reflectance, clearly manifested in the figure corresponding to the NIR.

NIR reflectance is strongly correlated with the volume of intercellular air spaces in the mesophyll layer of leaves (Gausman *et al.*, 1970). As the water fills the air gaps, the refractive index discontinuities are reduced and there is a resulting decrease in multiple scattering. This increases transmittance and reduces reflectance. Thus, diminished shadowing in NIR is noticed in comparison to the red region (Venderbilt, 1985, Deering and Eck, 1987). Angular effect is higher in red than that in NIR (Breece and Holmes, 1971). However, in the NIR region, where multiple scattering reduces the back-shadow effect, the wheat reflectance in the forward scattering shows major gap effect.

Figure 4b shows the plot of NIR directional reflectance as a function of different dates for varying viewing angles in the principal plane. While, figure 4c shows the change in NIR reflectance between consecutive measurements dates as a function of different dates for varying viewing angles in the principal plane. For a given date, change in red reflectance $\delta\rho_{nir}$ has been calculated by subtracting the NIR reflectance value on the immediate earlier date from the reflectance value on the date considered. A positive change indicates an increase in NIR reflectance, while the negative value indicates a decrease in NIR reflectance. These figures reveal that the sensitivity of NIR reflectance to wheat growth sequences is significantly influenced by the angle of observation.

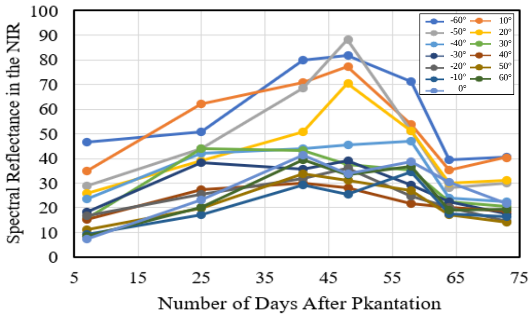

Fig. 4b: Same as in Figure 3b, except for the NIR spectral region (0.76-0.90 μm).

Reflectance in the forward scattering direction exhibits relatively less sensitivity and backward scattering direction shows the highest sensitivity particularly for viewing angle around 40°. Comparison of reflectance patterns shows that red reflectance has a bowl shape whereas NIR reflectance has a hill shape. In this case there is a tendency for the light intercepted by the canopy to be multiply scattered onto the soil surface thus reducing the angular dependency. In contrary to red reflectance, NIR reflectance undergoes to continuous changes over the entire life cycle except the last two measurements in the NIR exhibit no appreciable changes. While a slight increase is noticed in bidirectional reflectance in the red spectral region measured on the last two consecutive dates March 11 and March 21 representing the senescent period.

At the early stage of the wheat crop as on the 15th January, reflectance pattern of the wheat canopy was appreciably biased by the soil-background. During the early growth period of wheat crop as on the 31st January, canopy reflectance increases gradually as the vegetation develops through an increase in leaf density and canopy thickness. At this stage, vegetation cover was relatively thin and most of the radiation in the near-infrared wavelength penetrated through thin leaf layer. However, with the passage of time, canopy thickness increased that resulted in an additive effect on reflectance. Part of the radiation transmitted by the first leaf layer is reflected back by subsequent layers (Hoffer, 1978) and causes an increase in canopy NIR reflectance. However, after a certain number of leaf layers, addition of extra layers does not increase near-infrared reflectance.

Time varying crop growth sequences associate dynamic changes in the properties of canopy elements as well as in the thickness and coverage of vegetation. Leaf reflectance in the near-infrared region increases with maturation (Gausman et al. 1970). Perhaps, the increase in cell wall-air interfaces provides greater opportunity for increased multiple scattering of radiation. Such a trend is continued up to 7th February. Reflectance value at nadir under bare soil condition (just before plantation)

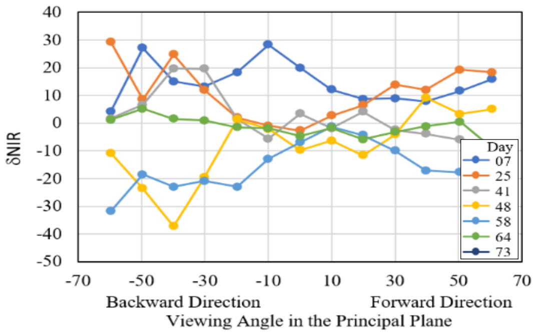

Fig. 4c, Same as in 3c except, for the NIR spectral region (0.76-0.90 μm).

was only about 0.183. While reflectance exhibits a value of about 0.386 at nadir on the 15th January and a value of about 0.40 on the 7th February. That is increases of about 110.9% and 118.6% are noticed for the data acquired on the 15th January and 7th February respectively.

Comparison of date-wise NIR reflectance (Figure 4b) and crop height (Figure 2) demonstrates that crop height was increased from a value of 56.2cm on the February 17 to a value of 85.9 cm on the February 17, i.e., an increase of about 29.7 cm (≈53%) while the NIR reflectance was decreased from a value of 39.9 to a value of 29.2, i.e., a decrease of about 9.8 (≈25%) was occurred during the same period of time. At a certain phenological stage of wheat development, called ‘‘booting,’’ the lower leaves of a plant begin to turn brown, due to a loss of chlorophyll (Anatoly et al., 2002). The result is a decrease in the number of actively reflecting leaf layers, with a consequent decrease in NIR reflectance (Leamer et al., 1980). Tucker et al. (1981) showed the decrease of NIR reflectance around the booting stage when vegetation fraction was over 60%. In agronomic crops, NIR reflectance levels off or even decreases with an increase of vegetation fraction (Kanemasu, 1974). NIR reflectance decreases as a result of a change in leaf orientation, from predominantly horizontal to predominantly vertical, at a certain stage in the growth cycle (Colwell, 1974; Jackson and Ezra, 1985).

At the initial stage of senescence, near-infrared reflectance increases as cell walls pull apart and are reoriented, resulting in an increased number of cell wall-air interfaces (Daughtry and Biehl, 1985) and reflectance decreases with advanced senescence. The decrease in the number of cell wall-air interfaces that accompanies the collapse of cells and the reduction of air spaces decreases the reflectance. In general, internal stress due to continuing enlargement of the epidermal cells situated above the mesophyll cells pulls mesophyll cells apart. Such an effect results in an increasing amount of spongy mesophyll and thereby, causes an increase in NIR reflectance (Myers, 1983). Young leaves tend to have a more compact mesophyll. Intercellular air spaces are developed with leaf expansion when leaf size is 25-33% of a fully-grown leaf (Myers, 1983) and is significantly influenced by the aging factor.

A fundamental difference between the angular pattern of wheat canopy reflectance in the red and NIR region is that appreciable changes in canopy reflectance occurs throughout the life cycle in the NIR region, whereas, no appreciable changes occur during the middle phase of the wheat life cycle. Another important point is to be noted that the differences in reflectance value between different growth stages is maximum in the backscattering direction at about 40°. This suggests that as temporal changes in wheat crop produces maximum contrast between observations on different dates, observation near this viewing angle will provide effective information regarding the growth of the plant.

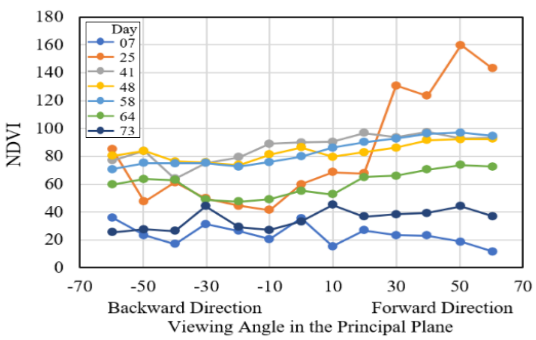

Fig. 5a: Normalized Difference Vegetation Index (NDVI) as a function viewing angle in the principal plane for a wheat canopy on different dates, 15th January, 31st January, 7th February, 17th February, 11th March and 21st March. The solar zenith angles correspond to 48°, 46°, 44°, 47°, 37° and 38° respectively.

Normalized Difference Vegetation Index (NDVI)

Various authors reported the angular effects on the normalized difference vegetation index as derived from directional canopy reflectance data (e.g., Luo et al., 2003; Deering and Eck, 1987; Holben et al., 1986; (Islam et al., 2016; Sultana et al., 2019; Tazneen et al., 2021; Panchal et al., 2021). Figure 5a shows the variation in NDVI as a function of viewing angle in the principal plane for the wheat crop at different dates covering the crop life cycle including early, middle and senescent stages. Viewing angle ranges from 60° in the backward direction to 60° in the forward scattering direction. Figure 5b shows the variation of normalized difference vegetation index (NDVI) as a function of different dates covering the life cycle of wheat crop under different viewing angles. While, Figure 5c shows changes in normalized difference vegetation index (δNDVI) between consecutive dates of measurement as a function of time covering the wheat life cycle under different viewing angles. For a given date, change in red reflectance δNDVI has been calculated by subtracting the NDVI value on the immediate earlier date from the NDVI value on the date considered. Angular NDVI pattern of wheat canopy exhibited an orderly fashion throughout the growing season of the plant from early to senescent phases. For all the dates, increase in NDVI is noticed for viewing angles starting from 20°-30° in the backward scattering direction up to 60° in the forward scattering direction.

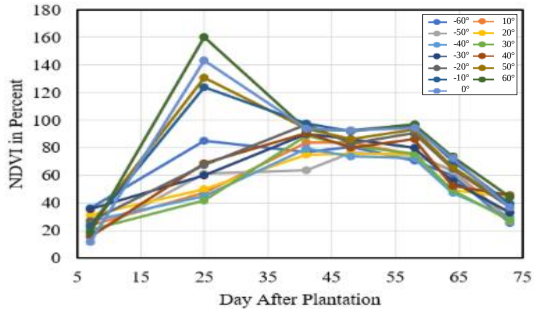

Fig. 5b: Variation of NDVI for the wheat canopy as a function of number of days after plantation covering from early to near harvesting stages for different viewing angle in the principal plane. The dates correspond to 15th January, 31st January, 7th February, 17th February, 11th March and 21st March. The solar zenith angles correspond to 48°, 46°, 44°, 47°, 37° and 38° respectively.

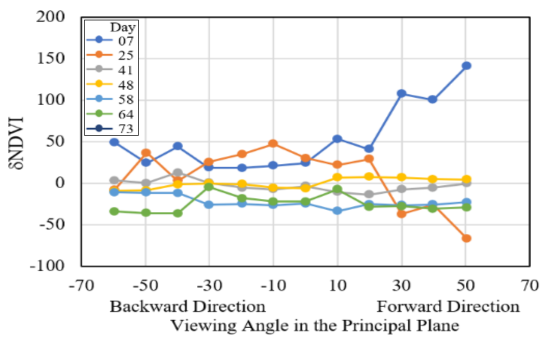

Fig. 5c: Changes in the value of normalized vegetation index (δNDVI) as a function number of days after plantation covering from early to near harvesting stages for different viewing angle in the principal plane. For a given date, change in NDVI value (δNDVI) has been calculated by subtracting the NDVI value on the immediate earlier date from the NDVI value on the date considered.

Comparison of angular patterns of NDVI and red and

NIR reflectances show that angular effect is largely minimized though red and NIR reflectances have significantly variability particularly in the backward scattering direction. Moreover, NDVI increases from the larger viewing angle in the backward scattering direction in the principal plane towards forward scattering direction. Whereas in the red and NIR, an opposite trend of reflectance is observed. The observed decrease in NDVI in the backscatter direction can be explained by the higher reflectance anisotropy for visible wavelengths than in the NIR (Lobel et al., 2002). Such a condition results in a decreased contrast between red and NIR reflectance as shade becomes less prominent (e.g., Deering *et al*., 1999).

NDVI showed a curvilinear response that saturated for high vegetation density as already was reported by various authors (Asrar et al., 1984) and thus largely restricts the applicability of NDVI for well-developed canopies. On the other hand, NDVI was more sensitive for low LAI, which makes it more suitable for assessing crop growth at the initial stages. Non-green components contribute to the canopy spectral reflectance, and NDVI has been reported to vary due to the presence of non-green vegetation (Bartlett et al., 1990; Leeuwen and Huete, 1996) and due to soil background (Nyamekye et al. 2021; Huete, 1988). NDVI value was minimum for bare soil condition (just before plantation) about 0.130. With the passage of time after plantation, NDVI value gradually increased and reached to a value of about 0.608 on the 15th January. During the early stage of the crop, most of the absorbed radiation in the photosynthetically active region was used to maintain the growth of the crop. NDVI then attained its maximum value of about 0.827 on the 31st January i.e., 40 days after planting. After that, NDVI gradually decreased as on the 17th February about 0.719 and on the 11th March about 0.494 and finally reached to a value of about 0.263 on the 17th March.

Here it should be mentioned that after attaining the maximum growth, the absorbed radiation was mainly used for the production and development of seeds upto the near harvesting stage. Consequently, the time integral of NDVI over the crop life cycle is an important indicator regarding crop yield. Crop phenological changes as accompanied by variations in canopy LAI, aboveground biomass, and pigment concentration have caused significant changes in the canopy spectral signature.

Comparison of figures 3a and 5a reveals that temporal pattern of NDVI has a hill shape, while bidirectional reflectance in the red spectral region has a “bowl shape”. Unlike the red and NIR bidirectional reflectances, temporal NDVI pattern covering different growth stages exhibited near similar sensitivity (Figure 6a) to observation made under different viewing angles. This was due to minimization of angular effect in NDVI. In fact, in NDVI, non-Lambertian effect is partially eliminated due to high linear correlation between LAI and reflectance both in the red and near-infrared spectral regions (Lee and Kaufman, 1986). NDVI value represented significant variation with time particularly from the early to fully-grown stage up to 50 days after plantation. Apart from that time, NDVI value demonstrated relatively stable behaviour for the rest of the crop life cycle. Angular variation is largely minimized during the middle stage up to the near harvesting period.

Referring to figure 5b it should be noted that at the initial stage of wheat growth, the derived NDVI pattern exhibited two characteristically different trends depending on the viewing geometry. For observation particularly from the backward scattering direction, an increase in NDVI value is noticed between consecutive measurements performed around 40 days after planting in comparison to measurement after 15 days of planting. While, a decrease in NDVI value is noticed for measurements performed from the forward scattering directions on the same consecutive dates. From figures 4b and 4c another point is to be noted that the major variation in NDVI value was occurred during early stage of wheat life cycle. This is quite consistent with the well-established fact that NDVI is more sensitive during the growth phase of a canopy in comparison to its mature stage particularly corresponding to measurement around 50 to 60 days after planting. As the crop reached toward senescence stage, NDVI value dropped down due to decreased chlorophyll activity in the red region that resulted in an increase in red reflectance and at the same time due to decrease in NIR reflectance as a consequence of degradation of canopy architectural properties.

Conclusions

Recent advancements in the space-based data acquisition technology and diversity in sensor characteristics have opened a new era in the retrieval of information on the earth’s surface properties. Various space-based remote sensing instruments are regularly generating huge amount of data. Eventually, better understanding of the characteristics as well as the dynamic variability of such radiative measurements is very much essential to maximize the advantage of this space-based technology. Complex biophysical radiative transfer processes are usually involved in the determination of radiative responses. Liveliness of spectral reflectance in relation to phenological development of a crop canopy offers the opportunity to use such radiative measurements for the retrieval of valuable information. In order to fully accomplish the objective of information retrieval, the possible relationships between radiative measurements and different geo-biospheric parameters intervening during the course of interaction have to be properly apprehended. In the present paper, effects of temporally changing crop condition on the directional response characteristics of a wheat canopy have been studied over the crop life cycle in view of monitoring growth and development of crop using directional measurements of reflectance.

The present study reveals that radiative transfer through wheat canopy is largely influenced by the temporal growth sequences due to changes in vegetation structural and optical properties at different stages. Phenological changes driven by biological growth rhythm of wheat results in a systematic variation in directional reflectance in red and NIR regions. Angular patters of red and NIR reflectance are characterized by relatively high surface reflectance near the larger viewing angle in the backward scattering direction that gradually decreases towards forward scattering direction. Moreover, an increase in directional reflectance is noticed near larger viewing angle in the forward scattering direction for sparse to dense vegetation while no such increase is evident for bare soil condition. At the early stage, non-irrigated condition of wheat field resulting in relatively bright soil background influenced the overall directional reflectance value. Phenomenon of hot spot is also observed in the angular pattern of measured directional reflectance. Temporal analysis depicts that gradual transformation of bare land into vegetated area with increasing coverage and density of vegetation results in increasingly lower value of surface reflectance in the red due to high absorption of solar radiation particularly in the photosynthetically active region. While, relatively high directional reflectance is resulted in due to high scattering by canopy elements in the near-infrared. During senescent phase, chlorophyll activity became minimum and the leaves became dry as a result red reflectance increases and NIR reflectance decreases and thus the contrast between reflectance in the red and NIR regions was decreased.

Analysis of sensitivity of red and NIR reflectance to crop growth sequences implies that larger viewing angle in the backward scattering position is relatively more sensitive than that in the forward scattering direction. Temporal pattern shows increasingly flattened behaviour of directional reflectance for viewing direction from extreme backward towards extreme forward scattering direction in the principal plane. In red and NIR regions, temporal dynamics of reflectance is modulated by the directional aspect of radiation. While, directional effect is largely minimized in NDVI as compared to individual red and NIR reflectance. However, temporal variability is still preserved in NDVI as depicted in the temporal NDVI pattern. Both amplitude and angular pattern of directional reflectance are influenced by the crop growth sequences. In case of reflectance in the red spectral region, changes are mostly concentrated from the early to middle growth stage. While, variation in reflectance in the NIR region occurred during the entire life cycle of the crop. In case of NDVI, early part of the growth cycle was more sensitive. Temporal pattern of NDVI exhibits a systematic variation over the life cycle of the crop with an inverted U-shaped temporal pattern.

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