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Biophysical Parameters Retrieval and Sensitivity Analysis of Rabi Crops (Mustard and Wheat) from Structural Perspective

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Abstract—The sensitivity of dual-polarized Sentinel-1 backscatter towards biophysical parameters (height and biomass) of wheat and mustard crops was investigated. The plant height and biomass observations categorized into three groups were useful in understanding the sensitivity across a particular biomass and height range whose significance was determined using a statistical measure (student's t-test). The crop parameters were retrieved only for the C-band sensitive biomass ($< 5\,\mathrm{kg\ m^{-2}}$) and height ($< 160\,\mathrm{cm}$ for mustard and $< 80\,\mathrm{cm}$ for wheat) range considering the saturation of signals at advanced crop stages and based on the detailed investigation. The sensitivity towards the mustard plant height becomes very weak as the crop proceeds to a height $> 190\,\mathrm{cm}$. A low RMSE (11.50 cm) was observed when the retrieval was done for height $< 160\,\mathrm{cm}$. The cross-polarized responses were more sensitive to crop biomass than co-polarized responses mainly due to the dominant depolarization of the transmitted power. An early saturation was found at co-polarized VV ($4\,\mathrm{kg\ m^{-2}}$) as compared to cross-polarized VH ($6\,\mathrm{kg\ m^{-2}}$) particularly for planophiles like mustard and little later in the case of erectophile such as wheat. The backscatter response was found to be sensitive at early crop stages for both the crop geometry, and hence retrieval of biophysical parameters at these stages can yield better accuracy than the overall retrieval. The retrieval of wheat height resulted in a low RMSE of 9.25 cm when the retrieval was carried out for crop height $< 80\,\mathrm{cm}$. Retrieval was attempted using the simplistic logarithmic model which can find ways in the operational application using wide swath dual-polarized datasets.

1. INTRODUCTION

With increasing world population and thereby increasing global food demand, crop monitoring is very crucial for ensuring food security for which Remote Sensing data have exhibited great potential. Crop biophysical parameters, such as biomass, height, leaf area index (LAI), and vegetation water content (VWC), can be used to determine the crop vigour and are vital inputs for crop yield models [1, 2]. [3, 4] have extensively used Remote Sensing data for accurate mapping and quantification of biophysical parameters as there exists a high correlation between these parameters and the observations derived from satellite data. Synthetic Aperture Radar (SAR) data due to various advantages associated with it such as all-weather observation, multi-frequency, multi-polarization, and sensitivity towards different crop parameters are highly suitable for crop monitoring. SAR data have been considerably used in a wide range of agricultural applications. [5–8] have used SAR data such as ERS-1, Radarsat, ENVISAT-ASAR, and Sentinel for crop mapping. The capability of microwave data for crop classification has also been extensively explored by many researchers in the past [9–11]. Microwave remote sensing data have also revealed great potential in crop yield estimations [12–14]. A number of techniques such as SAR backscatter analysis, SAR polarimetry, and SAR interferometry have been employed

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for crop studies. Temporal backscatter dynamics that largely depend upon the crop geometry, biomass, dielectric properties, and density [15] have been extensively studied to evaluate its potential in crop identification and monitoring [16–18]. The polarimetric SAR (PolSAR) data that contain information about polarization amplitude, as well as phase of the target, have been widely used for crop characterization and classification [19–22]. The PolInSAR data that include the intensity, polarimetric, and interferometric information provide a large amount of information and are useful for retrieving crop parameters such as crop height [23].

Apart from the above-mentioned applications of SAR data, there exists a great potential of microwave remote sensing data for crop parameter studies because of its sensitivity towards crop parameters such as biomass, moisture content, height, LAI, and density. The sensitivity of parameters derived from SAR data to crop biophysical parameters has been reported in many previous studies using different techniques. [24] investigated the interaction of SAR backscatter with rice growth variables at multiple frequencies and the inferred significant correlation of LAI and biomass at C and L bands, with poor correlation at higher frequency (Ka, Ku, X) bands. [25] used multi-temporal, multi-incidence angle Radarsat data to study the correlation of backscatter with crop growth parameters and found a better correlation to crop height at shallow incidence angle ($> 40^\circ$) than steep angle (23°). [26] exhibited the potential of polarimetric parameters such as entropy (H), mean scattering angle (α), and polarimetric decompositions in crop biophysical parameters retrieval using fully polarimetric Radarsat-2 data. [18] used multi-parametric SAR data to study the correlation between SAR backscatter and crop height and inferred high correlation at L band as compared to C band particularly at advanced crop stage. Researchers have also investigated the polarimetric SAR interferometry for crop biophysical parameter studies [23, 27].

Though crop biophysical parameter retrieval using quad-polarized SAR data has been extensively addressed, crop parameter studies using dual-polarized SAR data need more attention especially with the launch of a dual-polarized (VV and VH) Sentinel satellite constellation system. Sentinel 1 is currently the workhorse globally that provides an unprecedented temporal and spatial resolution radar data with a large swath and free accessibility to large datasets. The dual-polarized data are of great importance particularly when acquiring polarimetric datasets over large swaths may be difficult. The objective of the present study is to analyze the sensitivity of backscatter at VV and VH polarizations derived from Sentinel 1 SAR data to *Rabi* crops (Wheat and Mustard) biophysical parameters such as crop height, fresh biomass, and density. The methodology and validation will have implications for future RISAT-1A to be launched in the next year.

2. STUDY AREA AND DATASETS

2.1. Study Area

The Central State farm (CSF) and the surrounding area of CSF in Hisar district (29.17 N, 75.78 E), Haryana of Northern India was selected as the study area (Fig. 1). It covers an area of about 3,983 km^2. The crop samples were collected from Central State Farm (Fig. 2) and its surrounding located in Hisar, Haryana. The farmland lies between 29°11'N–29°20'N latitudes and 75°36'E–75°45'E longitude and is of considerable size. The large experimental crop fields are maintained for seed generation and distribution to farmers. Paddy, maize, cotton, and pulses are the major crops grown in *Kharif* (summer) season, whereas wheat, sugarcane, mustard, gram, and peas are the main *Rabi* (winter) crops grown in the area. The state falls under the Trans Gangetic Plains Agro-climatic zone, and therefore, this approach of retrieval can be used in Northern and North-western parts of the Indian subcontinent including Northern India and neighboring countries.

2.2. Datasets

The Sentinel 1A and 1B is a two-satellite constellation that supplies dual-polarizations (VH and VV) at an unprecedented temporal and spatial resolution operating at C-band frequency (5.404 GHz) with a spatial resolution of 20 m and a revisit cycle of 6 days. The freely accessible temporal datasets used in the study were downloaded from (https://scihub.copernicus.eu). The potential of these datasets for crop monitoring is well known and has been investigated in many previous studies. Additionally, a field

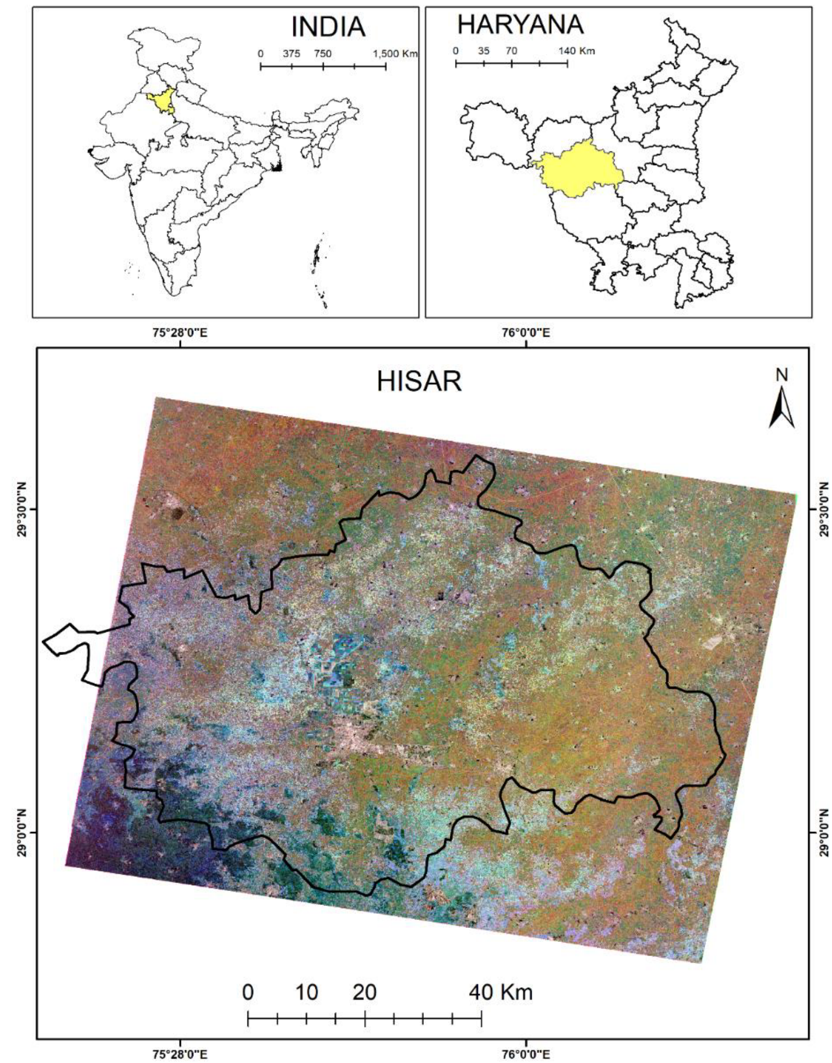

Figure 1. Study area Map and RGB (Red-VH 29 December 2018; Green-VH 22 January 2019; Blue-VH 27 February 2019) composite of cross-polarized backscatter.

survey synchronous to satellite pass was conducted to collect crop parameter information such as crop growth stage, crop height, density, crop vigor, fresh biomass, and also record their geolocation.

2.3. Materials

The crop biomass, height, and density observation were recorded during the field campaign. The plant biomass and height observations were categorized into three groups as illustrated in Table 1. The plant height and biomass ranges for the different groups were decided based on the variation in backscatter across crop height and biomass such as saturation of the backscatter at that particular crop height and biomass range/value.

3. METHODOLOGY

Multi-temporal Sentinel 1 SAR data were acquired from the open-access European Space Agency data hub. The temporal datasets were processed using SNAP software (Science toolbox exploitation platform, ESA). Orbital files were applied followed by radiometric calibration, speckle filtering, and Range Doppler

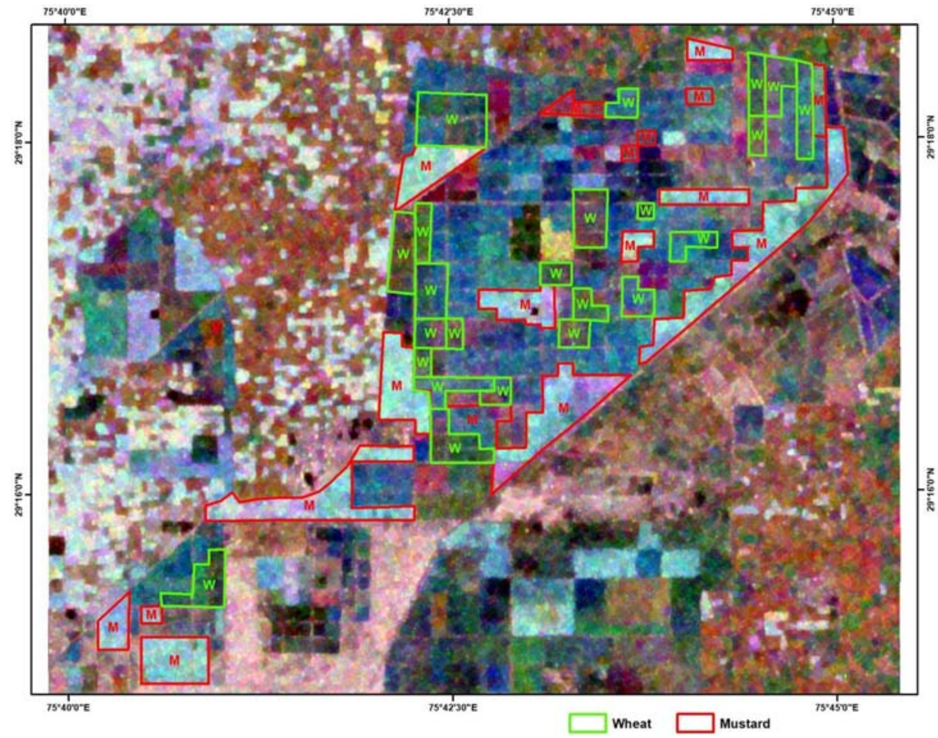

Figure 2. RGB composite (Red-VH 29 December 2018; Green-VH 22 January 2019; Blue-VH 27 February 2019) of Central State Farm, Hisar, Haryana.

Table 1. Crop biomass and plant height categories.

Group name	Mustard crop	Group name	Wheat crop
a	Plant height $< 140\,\text{cm}$	**x**	Plant height $< 70\,\text{cm}$
b	$140\,\text{cm} <$ Plant height $< 190\,\text{cm}$	**y**	$70\,\text{cm} <$ Plant height $< 100\,\text{cm}$
c	Plant height $> 190\,\text{cm}$	**z**	Plant height $> 100\,\text{cm}$
a′	Biomass $< 5\,\text{kg m}^{-2}$	**x′**	Biomass $< 4\,\text{kg m}^{-2}$
b′	$5\,\text{kg m}^{-2} <$ Biomass $< 10\,\text{kg m}^{-2}$	**y′**	$4\,kg\,m^{-2} <$ Biomass $< 8\,\text{kg m}^{-2}$
c′	Biomass $> 10\,\text{kg m}^{-2}$	**z′**	Biomass $> 8\,\text{kg m}^{-2}$

terrain correction. The VH and VV polarization channels were then converted to decibel (dB). The temporal datasets were coregistered to create a temporal stack. The various crop parameters collected during the field survey were used to find its correlation with SAR backscatter at both VH and VV polarizations (Fig. 3).

The crop biophysical parameters readings observed during the field survey were categorized into three groups (Table 2). The significance of the difference between the sample groups was examined using a t-test at 95% confidence level with derived parameter sigma naught (σ°) vs different crop heights and biomass. Based on the results of the sensitivity analysis, crop biophysical parameters viz. crop height and wet biomass were retrieved at their sensitive height and biomass range.

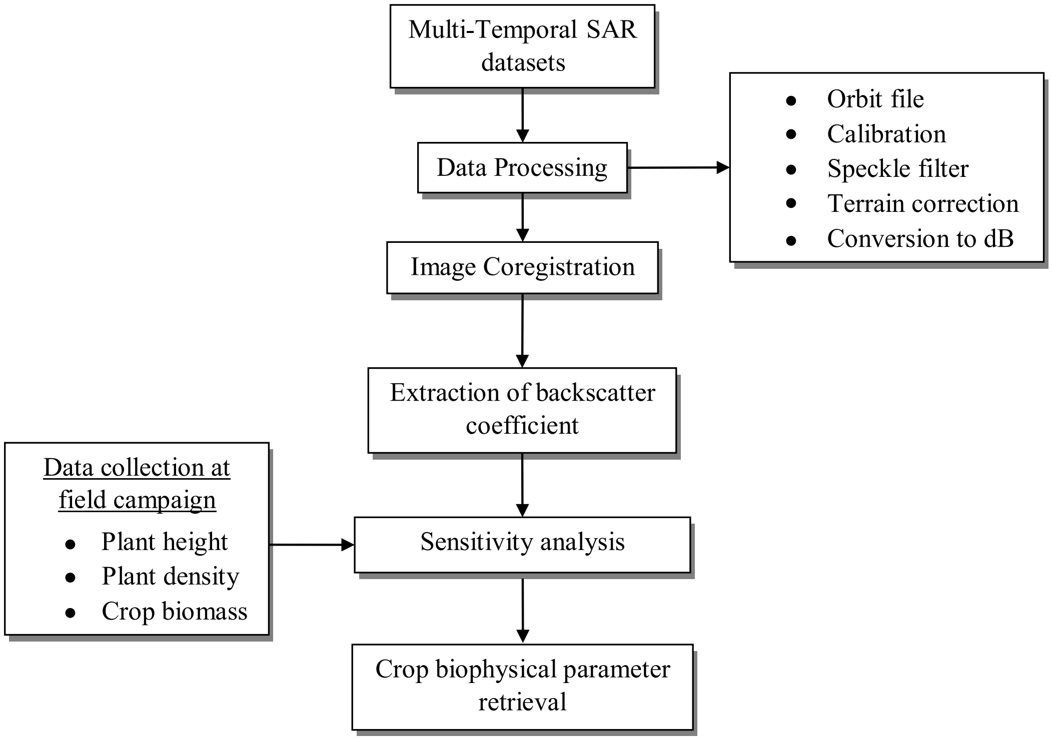

Figure 3. Methodology flow chart.

Table 2. Significance of difference between three groups of plant height and biomass using t-test at 95% confidence level.

Plant height (Mustard):	a: < 140 cm;	b: 140 to 190 cm	c: > 190 cm
Plant biomass (Mustard):	a': < 5 kg;	b': 5 to 10 kg;	c': > 10 kg
Plant height (Wheat):	x: < 70 cm;	y: 70 to 100 cm;	z: > 100 cm
Plant biomass (Wheat):	x': < 4 kg;	y': 4 to 8 kg;	z': > 8 kg

Crop	**Group**	**t-value**		**t critical value (two-tailed)**		**P value (two-tailed)**	
		VH	**VV**	**VH**	**VV**	**VH**	**VV**
Mustard	a & b	3.71	4.62	2.36	2.36	0.007	0.002
	b & c	2.16	0.84	2.16	2.20	0.05	0.41
	c & a	5.05	4.78	2.45	2.31	0.002	0.001
	a' & b'	3.81	2.80	2.06	2.06	0.000	0.009
	b' & c'	1.80	1.24	2.18	2.26	0.09	0.25
	c' & a'	6.15	3.41	2.08	2.12	0.000	0.004
Wheat	x & y	1.37	0.45	2.31	2.14	0.21	0.66
	y & z	2.28	1.68	2.31	2.23	0.05	0.12
	z & x	2.24	1.97	2.26	2.20	0.05	0.07
	x' & y'	3.11	2.54	2.16	2.10	0.008	0.02
	y' & z'	2.00	0.96	2.11	2.17	0.06	0.36
	z' & x'	2.03	2.87	2.16	2.13	0.06	0.01

4. RESULTS AND DISCUSSION

4.1. Crop Temporal Backscatter Profile

The interaction of crops with the incident microwave energy at their various growth stages results in dynamic backscatter values that depend upon crop geometry and dielectric properties. The temporal backscatter responses for mustard and wheat at VH and VV polarizations are illustrated in Figs. 4 and 5, respectively. The backscatter for mustard increases as the crop grows until the crop reaches a certain height and biomass range; thereafter. plateau was observed mainly due to the inability of the radar signals operating at C-band frequency to penetrate the crop canopy. The increase in backscatter was due to the increase in the volume of the scatterer as the crop grows which eventually depolarizes the incident radar pulses to a greater extent. The early sown mustard resulted in a higher backscatter (-12 dB at VH and -9.5 dB at VV) than late sown (-16 dB at VH and -14 dB at VV) during 29th December 2018 due to the difference in the phenological stage and the therefore different sizes of the scatterer. With the increase in plant height and biomass from 29th December 2018 to 22nd January 2019, the backscatter value increased during this period. A decrease in the backscatter was observed for early sown mustard progressing to maturity during 27th February 2019 (-10 dB to -13 dB at VH and -6 dB to -9 dB at VV) which further decreased (-18 dB at VH and -14 dB at VV) during 23rd March 2019 since the VWC of the plant decreases as the crop matured and dries near harvest. In the case of late sown mustard, the backscatter increased till the 3rd date, i.e., 23rd March 2019, one date later from the early sown mustard. Similarly, the dip in the backscatter for late sown mustard was observed during 23 March 2019, one date lag from the early sown (-10 dB to -17 dB at VH and -7 dB to -11 dB at VV) (Fig. 4).

On the other hand, the temporal backscatter response trend of wheat was reversed to that of mustard since the backscatter decreased as the wheat crop grew, which attributes to the higher absorption than the scattering of the incoming radiation (Fig. 5). [28] estimated the scattering parameters for different crops by partitioning the EM radiation to scattering, absorption, emission, reflection, refraction, etc. The nature of the canopy material can be indicated by Ω range 0.5–0.98 whether it was scattering such as mustard or absorbing as wheat. The backscatter at VH polarization

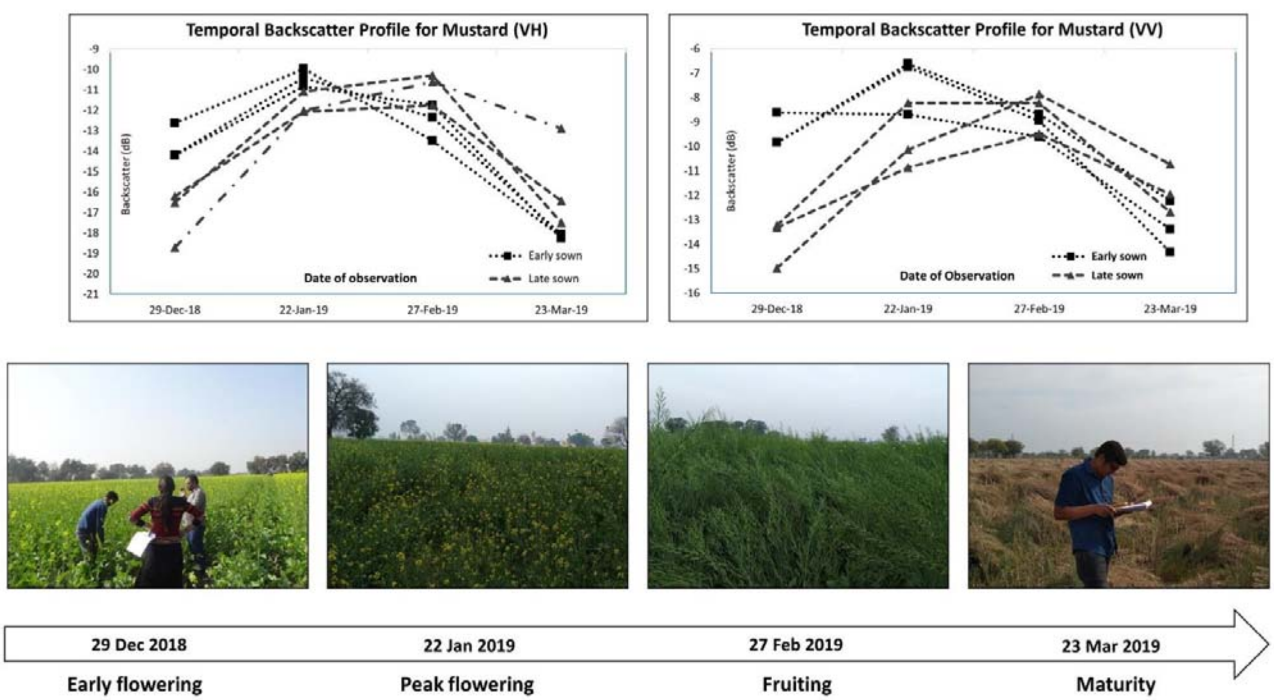

Figure 4. Temporal backscatter response of mustard.

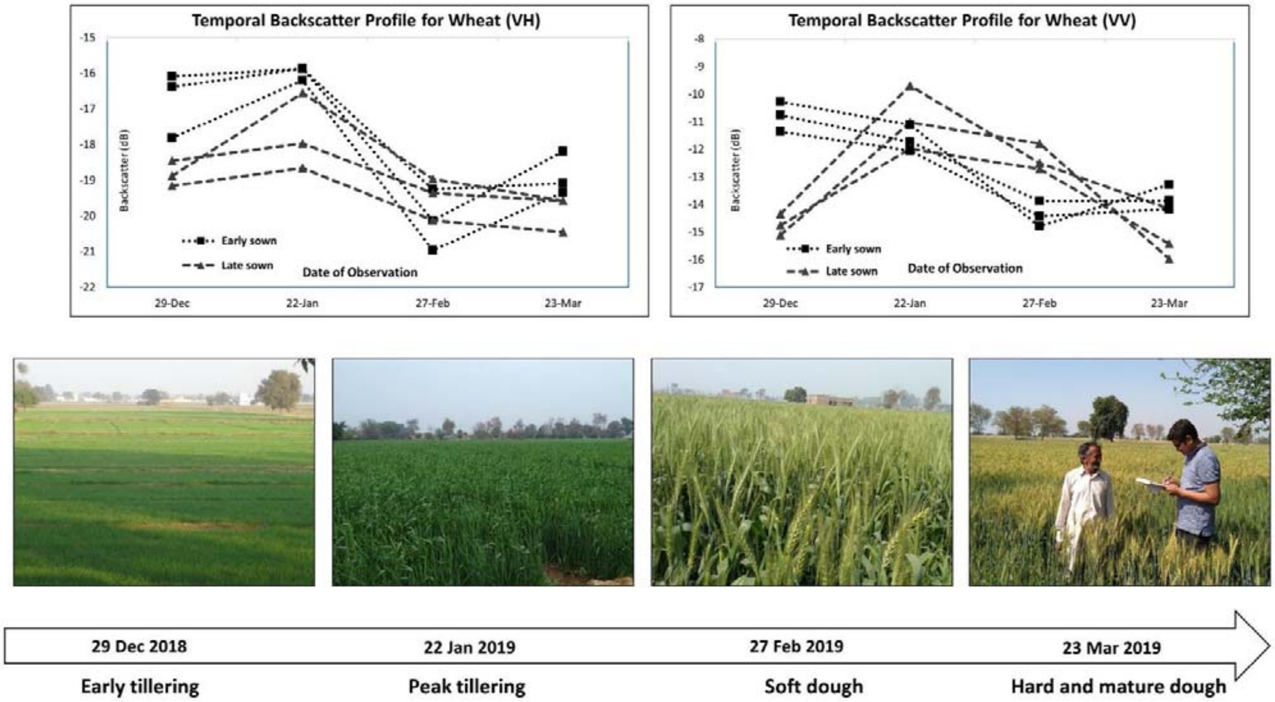

Figure 5. Temporal backscatter response of wheat.

increased between the first and second dates for both early and late sown wheats mainly because of the soil effect during the first date being dominated by the crop during the second date. The backscatter for early sown wheat was found to decrease for the second (22nd January; -12 dB) and third dates (27th February; -15 dB) for VV polarization due to absorption of the radar pulses by the wheat crop, whereas in the case of late sown wheat, the backscatter increased in the second date (22nd January; -10 dB) and decreased thereafter in the third (27 February; -13 dB) and fourth (23rd March; -15 dB) dates due to absorption effect by the canopy at advanced crop stage.

4.2. Students T-Test: To Test the Significance of Difference between the Three Sample Groups of Plant Height and Biomass

The crop biomass and height ranges observed during the field campaign were categorized into three groups for analysis (described in Table 2). The significance of the difference between the groups is examined using a t-test at 95% confidence level. The t-test is used for hypothesis testing, where the null hypothesis is either accepted (t-observed < t-critical value) or rejected (t-observed > t-critical value) based on t-value. In the null hypothesis, it is assumed that there exists no significant difference between the two populations. The threshold level was taken at a 95% confidence level ($\alpha = 0.05$). The observed t-value was compared against the t critical value (table value of t at different degrees of freedom). The null hypothesis cannot be accepted for any observed value of t that is greater than t-critical value, and therefore, the difference between the two sample groups is inferred. The backscatter value corresponding to plant height and biomass groups was the basis on which the difference between the plant height and biomass categories was decided. Calculated t-value for mustard was higher than t critical value for all groups except b' & c' which depicts that their grouping according to height and biomass has a significant impact in their backscatter responses, and hence groups a, b, and c are significantly different populations from each other. In the case of wheat, the calculated t-values for most of the categories were lower than the t critical value, and thus the backscatter responses corresponding to group x, y, and z are not different populations from each other except for x' and y' where the variation in backscatter range was observed to be significantly different. The second and third groups belonging to higher ranges of plant height and biomass cannot be treated as significantly different groups in this study using C-band, but we infer and propose that they will have different implications at higher wavelengths.

The t-test performed on three categories of plant height and biomass revealed that for mustard crop the variations in backscatter between groups a and b of plant height and a' and b' groups of biomass were significantly different, whereas the changes in the backscatter ranges for b & c and b' & c' are not significant enough. In the case of wheat, the significant variation in the backscatter ranges was only observed for groups x' and y' of biomass.

4.3.1 Sensitivity of Crop Height to SAR Backscatter

4.3.1.1 Mustard

The correlation between backscatter and mustard plant height is illustrated in Figs. 6(a)–6(h). The sub-parts (b), (c), and (d) illustrate the split analysis to find range wise sensitivity. The backscatter increased with increasing plant height at both VV and VH polarizations and was observed to be more sensitive to plant height at VH ($R^2 = 0.51$) polarization than VV ($R^2 = 0.40$) polarization. The higher sensitivity at the cross-polarized response was due to the depolarization of the incoming radar signals from the large volume of the scatterer and only the depolarized part being captured in the cross-polarized (VH) responses whereas in the case of VV most of the incoming signals are attenuated from the canopy architecture.

The returned radar echoes at VH polarization have high sensitivity towards crop height at earlier

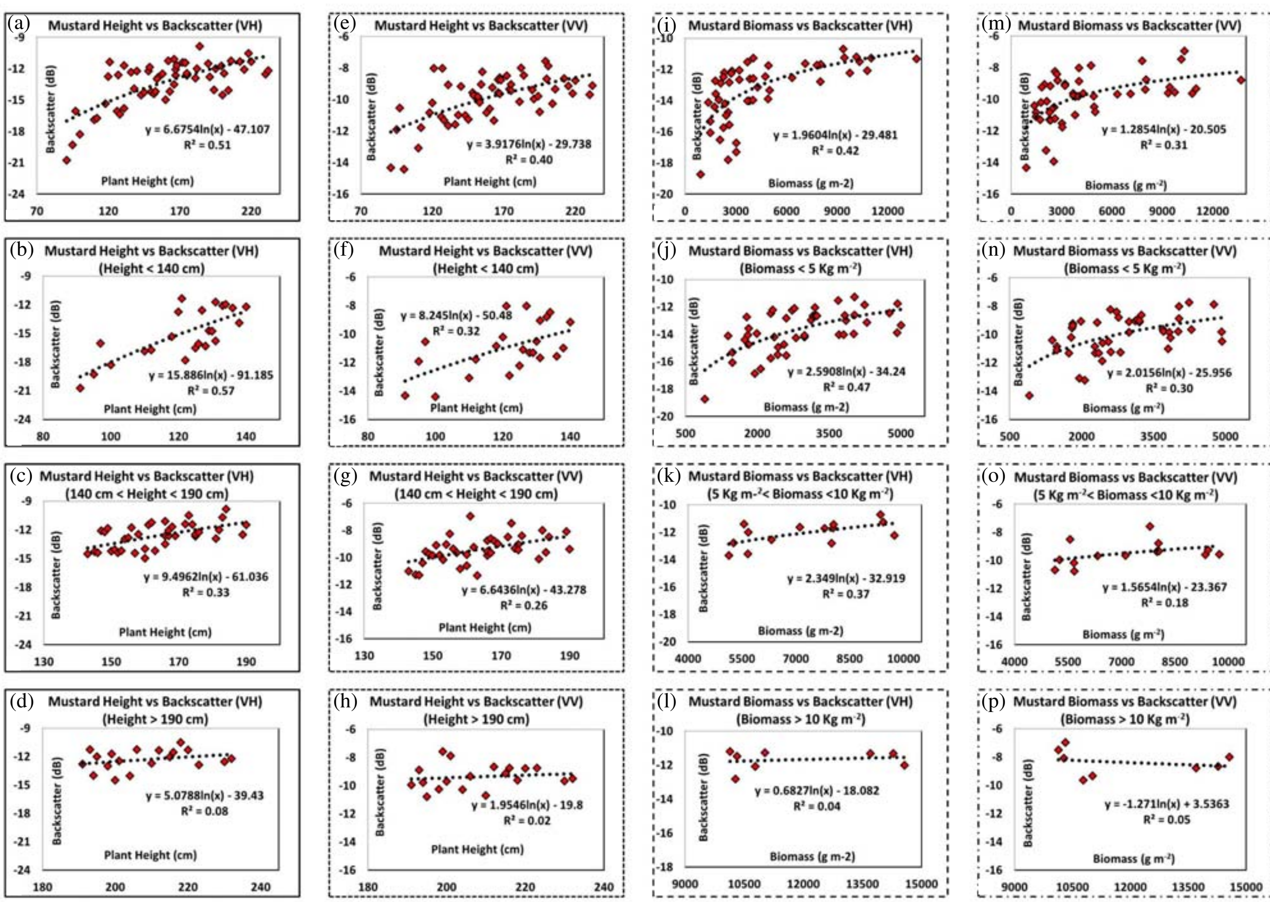

Figure 6. Scatter plot of mustard crop parameters and SAR backscatter. (a), (e), (i), and (m) overall crop stage; (row 2–4) various crop height and biomass range.

growth stages of the mustard crop (< 150 cm) (Fig. 6(b)), as backscatter increased dynamically (−19 dB to −13 dB) with increasing crop height ($R^2 = 0.57$). This rapid increase in backscatter response attributes to the faster canopy growth during initial stages as observed in planophiles. A low relationship was observed at VV polarization during the early stage due to the attenuation of the vertically polarized signal from the crop canopy (Fig. 6(b)). The sensitivity of the backscatter to plant height was found to decrease at the later crop stages that can be depicted by comparing the sub-parts of the main graphs of Fig. 6. A low to moderate correlation was observed for crop height between 140 and 190 cm at VH and VV polarizations (Figs. 6(c) and (g)) as the observed change in the backscatter range with an increase in crop height was low (−14 dB to −11 dB) during this height range because the volume/number of scatterers increased to a lesser extent during this stage.

For crop height of 190 cm and above, no significant change in the backscatter (−12 dB to −11 dB) was observed probably because the sensitivity of SAR backscatter at C-band frequency begins to decrease at advanced crop stages. A very low or no correlation between the crop height and backscatter was found at both VV and VH polarizations as the crop proceeds to a height greater than 190 cm. This was particularly due to the attenuation of radar signal at heavier canopy as the signal cannot penetrate deeper. This exhibits the need for deploying higher wavelength radar sensors (L and P) for crop parameter studies of high biomass crops, especially at their advanced stages.

4.3.1.2 Wheat

The scatter plots of wheat crop height and backscatter are illustrated in Fig. 7 where parts (b) to (d)

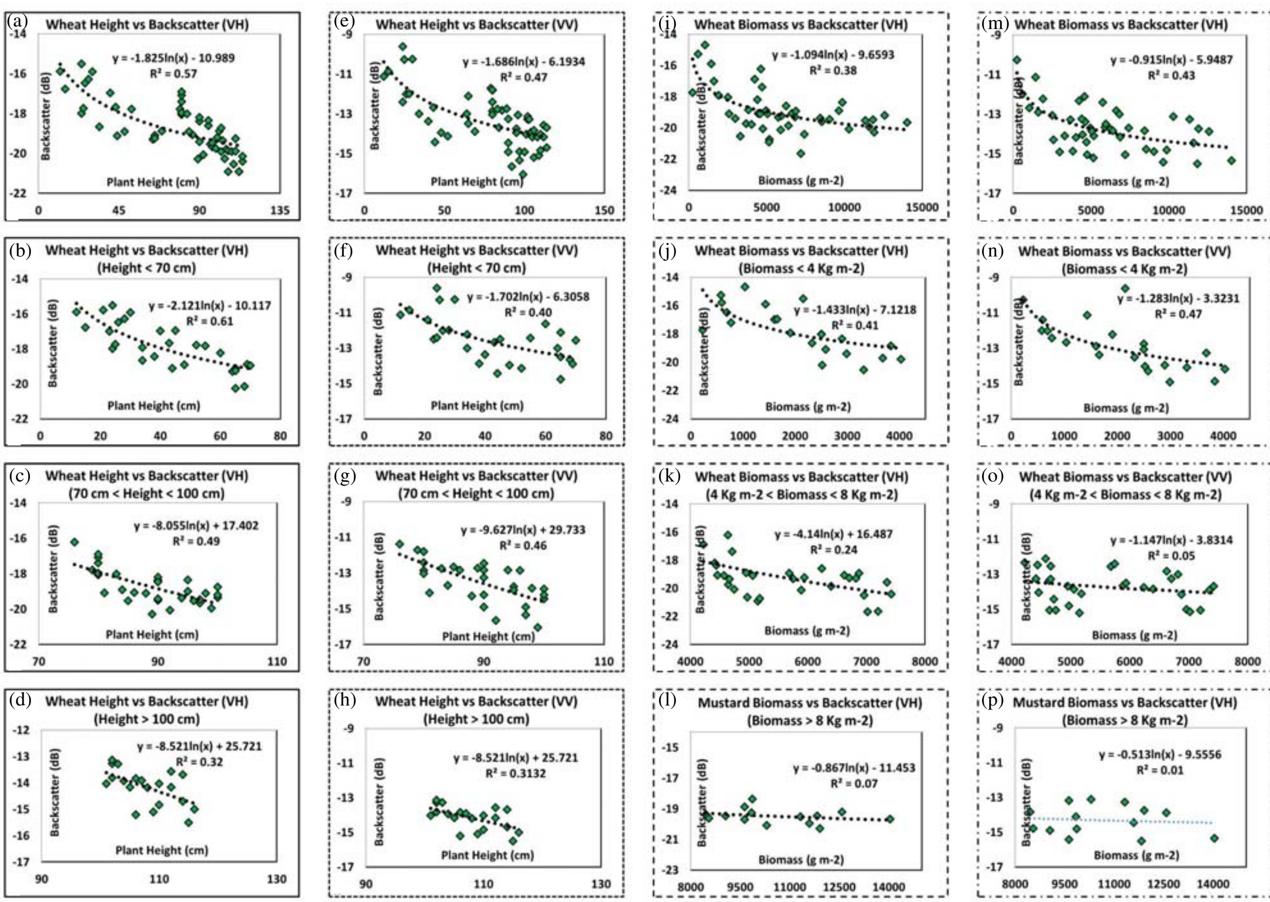

Figure 7. Scatter plot of wheat crop parameters and SAR backscatter. (a), (e), (i), and (m) overall crop stage; (row 2–4) various crop height and biomass range.

represent the plots at three distinct crop height ranges. The backscatters at VH and VV polarizations across the range of wheat plant height were observed to decrease with an increase in plant height. This reverse trend of decreasing backscatter with increasing plant height as compared to mustard is explained in [28]. The scattering parameters (α, Ω), attenuation parameter, and geometric parameter (G) are indicative of the canopy structure and vary through the different crops and their stages. The scattering parameters are estimated for different crops partitioning the EM radiation to scattering, absorption, emission, reflection, refraction, etc. The nature of the canopy material can be indicated by Ω range 0.5–0.98 whether it is scattering (paddy, mustard, cotton) or absorbing (wheat) [28].

A significant correlation between the backscatter and crop height was observed at both VH ($R^2 = 0.57$) and VV ($R^2 = 0.47$) polarizations (Fig. 7). A lower sensitivity at VV polarization was predominantly due to the attenuation of vertically polarized signals as it couples with the vertically oriented stems of wheat which is essentially an erectophile. A high sensitivity ($R^2 = 0.61$) of backscatter towards plant height was observed at early crop stages at VH polarization as the cross-polarized response was more sensitive to vegetation, whereas at VV polarization ($R^2 = 0.40$) a low sensitivity was observed because of weak response due to soil moisture and roughness (Fig. 7(b)). A moderate correlation between the backscatter and crop height was found at the advanced crop stages for both VH and VV polarizations (Figs. 7(c) and (g)). The correlation between the backscatter and crop height at VH polarization decreased as the crop advanced, whereas at VV polarization the correlation was observed to increase with advancement in the crop as with the increase in plant height the soil effect gets dominated by the crop.

Higher and similar sensitivity for both wheat and mustard was observed at VH polarization as most of the incident energy was depolarized from the plant canopy, and only the depolarized part was captured in the cross-polarized responses. A lower correlation at VV polarization for wheat was due to attenuation of the signal from the vertically oriented wheat plants whereas in the case of mustard the backscatter at VV polarization saturates due to high biomass of mustard.

4.3.2 Sensitivity of Crop Biomass to SAR Backscatter

4.3.2.1 Mustard

Mustard green/wet biomass inferred a positive relation with the backscatters at VV and VH polarizations. Cross-polarized ($R^2 = 0.42$) backscatter response was observed to be more sensitive to crop biomass than co-polarized ($R^2 = 0.31$) responses particularly due to depolarization of the incident radar pulses from the mustard canopy.

A moderate correlation at VH polarization ($R^2 = 0.47$) existed during the early crop stages (biomass $< 5000\,\text{g m}^{-2}$) as the backscatter increased significantly with an increase in crop biomass due to a rapid increase in the canopy of planophiles that dominantly contributes to the backscatter. The sensitivity of backscatter towards crop biomass lowers as the biomass increases further, and a low correlation ($R^2 = 0.37$) was observed at later stage (biomass range $5000\,\text{g m}^{-2}$ to $10000\,\text{g m}^{-2}$) as the variation in backscatter was minimal due to a lesser penetration of radar pulses at high biomass ranges mainly at C-band wavelength (Figs. 6(k) and (o)). The saturation of backscatter due to attenuation of radar signals is observed for crop biomass greater than $6000\,\text{g m}^{-2}$ at VH polarization, whereas early saturation (around $4000\,\text{g m}^{-2}$) was observed at VV polarization because of the quicker attenuation of the VV signal than VH due to heavy canopy growth of planophiles such as mustard (Fig. 6).

In advanced crop stages, the interaction of radar signals at C band is mostly limited to the top layers of canopy. Thus, any further increase in the crop biomass is not manifested in radar signals operating at C band and exhibits the need of deployment of sensors operating at low frequencies such as L and S-bands for the estimation of crop biomass for high biomass crops such as mustard and cotton, particularly at their advanced stages. Many previous studies have reported the saturation effect for crop biomass above $5.7\,\text{kg m}^{-2}$ for radar operating at C wavelength region [25, 28]. Further increase in the crop biomass is not manifested in terms of an increase in SAR backscatter.

4.3.2.2 Wheat

We observed a negative trend between backscatter and wheat crop biomass, and the backscatter decreased with an increase in crop biomass (Figs. 7(i)–(p)). At the early crop stages, particularly for biomass $< 1000\,\mathrm{g\ m^{-2}}$ high backscatter was observed because of the interaction of radar signals with the underlying tilled moist soil as the crop growth rate is slow during initial phases. A low to moderate correlation existed between both co-polarized ($R^2 = 0.38$) and cross-polarized ($R^2 = 0.43$) backscatter responses and crop biomass. The correlations between wheat biomass and backscatter at both VV and VH polarizations are similar, as the effect of attenuation of the vertically polarized signal was less prominent in the case of biomass than that in height.

During the initial phase (biomass $< 4000\,\mathrm{g\ m^{-2}}$), there exists a moderate relationship between the backscatter and crop biomass at both VV and VH polarizations (Figs. 7(b), (f)), but the backscatter responses at VV ($R^2 = 0.47$) polarization was more sensitive to crop biomass than VH polarization due to dominant absorption of the incoming energy as compared to scattering during this biomass range. The sensitivity for biomass $> 4000\,\mathrm{g\ m^{-2}}$ was observed to be higher at VH polarization owing to the depolarization of the incident energy due to the development of plant leaves and biomass. No significant change in the backscatter at both VV and VH polarizations was observed for crop biomass greater than $4000\,\mathrm{g\ m^{-2}}$. A low correlation between backscatter and crop biomass was observed for biomass range greater than $4000\,\mathrm{g\ m^{-2}}$.

At VV polarization, the sensitivity of backscatter towards planophile ($R^2 = 0.40$) was less than erectophile ($R^2 = 0.47$) across the same biomass range. This is because the vertically polarized signal can penetrate the canopy of an erectophile such as wheat at higher biomass ranges due to the vertically oriented crop geometry and architecture of an erectophile. In cross-polarized response as the number and size of scatterers are greater in planophiles, it will have a significant sensitive range till higher biomass than wheat which has a lower number of scatterers per unit volume and more absorbers particularly in the earlier stage.

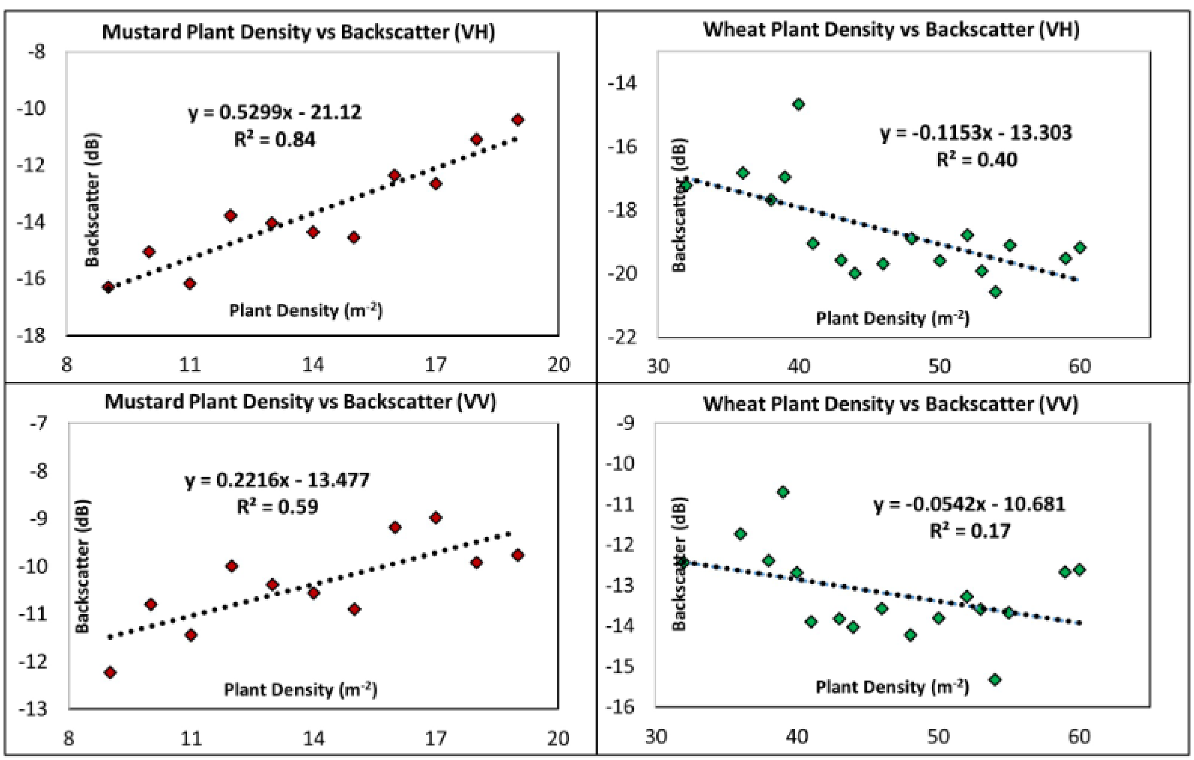

Figure 8. Scatter plot of mustard and wheat plant density vs SAR backscatter at VH and VV polarization.

4.3. Sensitivity of Crop Density to SAR Backscatter

The SAR backscatter from vegetated lands depends upon the crop volume and is therefore sensitive to varying crop density. Other than factors such as polarization, frequency, and incidence angle, the backscatter largely depends upon the volume and distribution of the scatterers. The backscatter response versus crop density of mustard and wheat is illustrated in Fig. 8. The variation in backscatter with varying density was prevalent for the mustard crop in comparison to wheat crop particularly at VH polarization due to depolarization of the radar signal by the vegetation volume. This infers that the sensitivity of backscatter to crop density was also dependent upon the polarization of the radar pulses. A high correlation ($R^2 = 0.84$) was observed between mustard plant density and backscatter at VH polarization and a moderate correlation ($R^2 = 0.59$) at VV polarization probably due to an increase in the volume and number of scatterers with an increase in plant density and thereby more depolarization of the incident radar pulses. The high correlation at cross-polarization was attributed to the varying backscatter response with the change in volume of the scatterer as the crop density increases. In the case of wheat, a higher dynamic range of backscatters at the cross-polarized ($R^2 = 0.40$) response was observed due to an increase in the volume of absorbent with an increase in density. A low correlation ($R^2 = 0.17$) with wheat plant density at VV was found as with the increase in density the attenuation of the vertically polarized signal from the plant component increases.

4.4. Crop Biophysical Parameter Retrieval Based on the Sensitivity Analysis at Various Height and Biomass Range

Crop biophysical parameters viz. plant height and biomass were retrieved by inverting the logarithmic model, selected during the sensitivity analysis. The biomass for both wheat and mustard crop was retrieved for 0–5 kg m^{-2}. The retrieval for mustard and wheat height was done for less than 160 cm and 80 cm respectively considering the sensitive range in C-band [25, 28]. The inversion of the model was carried out for the sensitive plant height and biomass range. The retrieved and observed crop parameters were compared on a 1 : 1 line plot to evaluate the accuracy of the model (Fig. 9). In the case of mustard, cross-polarized response was found to perform better than co-polarized response as

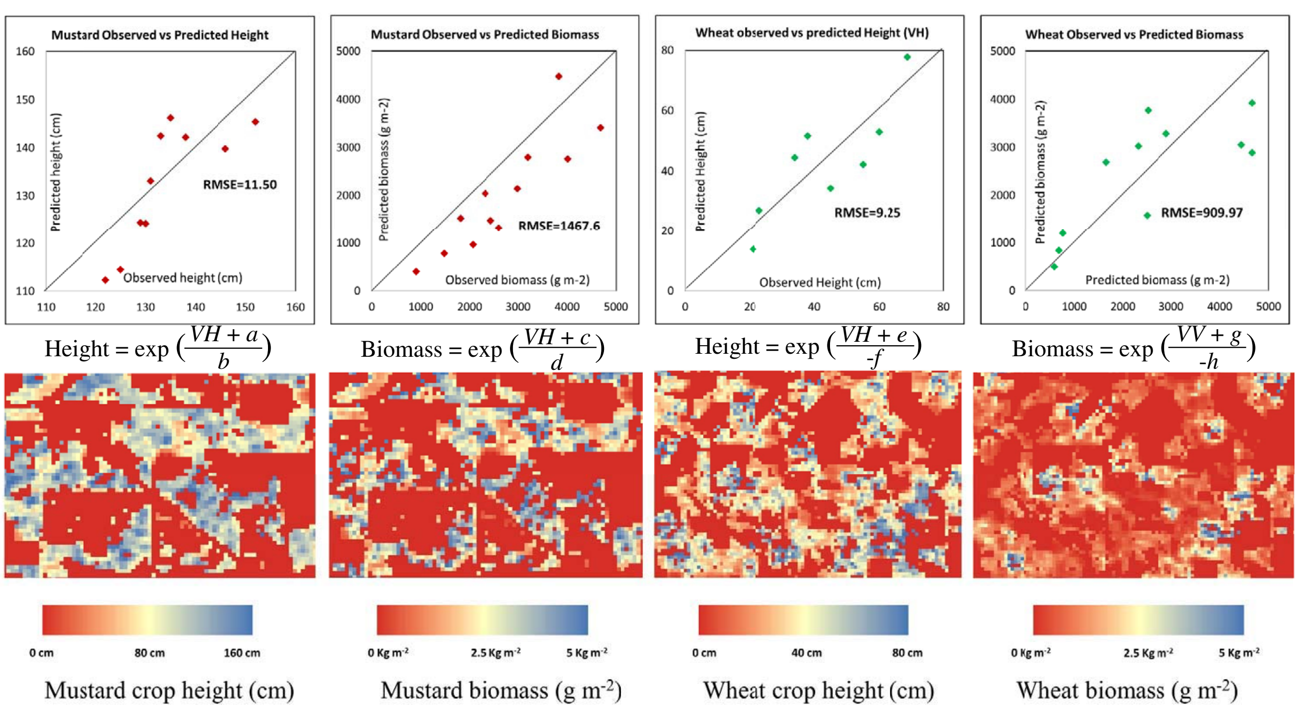

Figure 9. Validation plots and retrieval map of mustard and wheat biophysical parameters.

the VH backscatter was more sensitive to mustard height and biomass. The root mean square error (RMSE) in the case of mustard biomass was observed to be 1.46 kg m^{-2} when the retrieval was done using the VH response which increased to 2.4 kg m^{-2} with VV response. Similarly, in the retrieval of the mustard height, the model performed better for the cross-polarized response (RMSE = 11.50 cm) than the co-polarized response (RMSE = 19.55 cm). The logarithmic model was found to perform better at the initial crop stages (crop height < 160 cm and biomass < 5 kg m^{-2}) because the C-band signal is more sensitive at early crop stages. In the case of wheat, the crop biomass was estimated using the VV response as it was more sensitive at the early crop stages. The RMSE was observed to be 909.97 kg m^{-2}. VH response was found to be more sensitive to crop height and was therefore used for the retrieval. The retrieval of wheat height improved significantly (RMSE < 9.25 cm) when the model was used at early wheat stages. The retrieval carried out limiting the biomass (< 5 kg m^{-2}) and height ranges (< 80 cm) was observed to perform better.

5. CONCLUSION

The study appraises the sensitivity of different crop biophysical parameters such as crop height, biomass, and plant density towards dual-polarized Sentinel-1 SAR data. The backscatter for mustard increased with the advancement in crop due to dominant scattering phenomena from the crop canopy whereas a reverse trend was observed in the case of wheat due to dominant absorption as compared to scattering. The significance of the categorized plant height and biomass groups was made using a t-test, and the result revealed significant variations in the backscatter response for the different ranges of crop height and biomass. It gives a better understanding of the sensitivity across different biomass and height ranges in both the planophile and erectophile.

Higher sensitivity towards mustard height at the cross-polarized response ($R^2 = 0.51$) as compared to co-polarized response ($R^2 = 0.40$) was observed. VH response (RMSE = 22.98 cm) was found to perform better than VV response (RMSE = 26.89 cm) for mustard crop parameter retrieval. The sensitivity towards mustard plant height was lost as the crop proceeds to a height > 190 cm ($R^2 = 0.08$). Similarly, the sensitivity towards mustard biomass was higher at VH (RMSE = 1.79 kg m^{-2}) than the VV (RMSE = 3.02 kg m^{-2}) response. The backscatter response against mustard biomass saturated early at VV (4 kg m^{-2}) as compared to VH (6 kg m^{-2}). In the case of wheat, the backscatter at VH was more sensitive to wheat height than VV. The logarithmic model to retrieve height performed better with VH (RMSE = 23.8 cm) than VV (RMSE = 27.12) response. Similarly, in the retrieval of wheat biomass low RMSE values was observed at VH (1.76 kg m^{-2}) compared to that at VV (2.57 kg m^{-2}) polarization. The crop parameters retrieval for both wheat and mustard performed better at the initial crop stages where the crop height and biomass ranges were low. At the advanced crop stages, no significant change in the backscatter at both VV and VH polarizations was observed which denotes the saturation of backscatter response at that biomass range. A high correlation was observed between plant density and the backscatter response at VH and VV particularly for mustard crop ($R^2 = 0.84$ at VH).

A higher and similar sensitivity for both erectophile and planophile was observed at cross-polarization due to depolarization of the incident energy from the plant canopy, and only the depolarized part is captured in the cross-polarized responses. A lower correlation at co-polarization for erectophile was due to attenuation of the signal from the vertically oriented wheat plants whereas in the case of planophile the backscatter at VV polarization saturates due to high biomass of mustard. The observed correlation at co-polarized response across the same biomass range was observed to be higher towards erectophile ($R^2 = 0.46$) than planophile ($R^2 = 0.32$) due to the penetration capability of the vertically polarized signal at higher biomass ranges for erectophile.

In this zonation (grouping) of the response of the entire biomass and height range, the first two zones are retrievable using C-band dataset, but the third group (advanced stage) requires higher wavelength (L-band and/or S-band) data for more accurate retrieval in high biomass and height range.

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