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Research Paper

Analysing the potential of polarimetric decomposition parameters of Sentinel-1 dual-pol SAR data for estimation of rice crop biophysical parameters

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ABSTRACT

The potential of dual-polarization Sentinel–1 polarimetric decomposition parameters *i.e.*, entropy, anisotropy and alpha angle, to monitor the biophysical parameters of rice crop namely, fresh biomass, dry biomass, vegetation water content (VWC) and plant height is investigated in this study. Multi-temporal Sentinel–1A dataset during critical growth stages of rice was considered for regression analysis between the polarimetric decomposition parameters and the biophysical parameters using linear and logarithmic models. The best correlations are obtained at early vegetation stages of the crop *i.e.* between tillering to booting stages. The maximum value of Pearson correlation (R) is 0.82, found for VH polarization and plant height and maximum R^2 value obtained is 0.6 for linear regression of entropy and VWC followed by other biophysical parameters. The correlation of polarimetric decomposition parameters with biophysical parameters is not as high as that of VH backscatter coefficient. Multiple regression using various Sentinel–1 parameter yields a better correlation than regression using individual parameters. The maximum R^2 value of 0.765 is obtained for the multiple linear regression for VWC. Multiple regression using the backscatter coefficients and polarimetric decomposition parameters together gives a better correlation than that using only the backscatter coefficients. This indicate that the polarimetric decomposition parameters are sensitive to biophysical parameters and can be used as additional parameters along with the backscatter parameters for rice crop monitoring.

Keywords: Sentinel-1, Polarimetric decomposition, Entropy, Anisotropy, Alpha, Biomass

Crop monitoring using satellite data has become an important aspect in modern agricultural studies due to its potential in predicting plant conditions over large areas and enabling site-specific crop management or precision agriculture. In Indian context, one of the most important agricultural produces is rice (Oryza sativa) as it is the chief grain and is an integral part of the national economy. Owing to its large coverage and repetitive observational capabilities, satellite based optical remote sensing can be employed for rice monitoring during cloud free weather (Wiseman *et al.,* 2014; Dineshkumar and Satishkumar 2019). But for monsoon (*Kharif*) rice crop in India, remote sensing based on Synthetic Aperture Radar (SAR) that works in microwave region which is sensitive towards various geometrical and biophysical parameters of the crop, is most suitable due to its capability to operate in rainy & cloudy conditions and its penetration (Dave *et al.,* 2019; Haldar *et al.,* 2018; Harfenmeister *et al.,* 2021; Sharifi and Hosseingholizadeh 2020).

Various crucial phenological stages of rice can be monitored by SAR sensors due to its acquisition ability at multiple frequencies and polarizations (Prudente *et al.*, 2019). Many space agencies across the world have employed satellite-borne SAR systems operating at various frequencies, polarizations, swath and spatial resolutions for myriad applications. Various investigations have been done to study the relationship between the crop biophysical parameters and microwave SAR data at various frequencies (Wiseman *et al.*, 2014; Kumar *et al.*, 2017). The European Space Agency's Sentinel–1 sensors (1A and 1B), dual-polarization (VH and VV) SAR operating at C–band with high spatial resolution (10 x 10 m) and revisit period of 12 days for each sensor platform is freely

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available. For most agricultural applications, the SAR parameter that have been commonly used are the backscatter coefficients sigma naught (σ^0) (Vreugdenhil *et al*., 2018; Dineshkumar and Satishkumar 2019; Sharma *et al*., 2019; Kushwaha *et al*., 2022).

Originally, decomposition technique was formulated for full-polarimetric data such as RADARSAT–2, later the technique was extended for dual-polarimetric data such as those from Sentinel–1 albeit with some limitations (Cloude, 2007; Ji and Wu, 2015). The present study focuses on the capability of the polarimetric decomposition parameters of dual-polarimetric Sentinel-1 data in monitoring the biophysical parameters of rice crop namely, fresh biomass, dry biomass, Vegetation Water Content (VWC) and plant height, through its various growth stages. The multi-temporal dataset of Sentinel–1A dual-polarimetric data in the course of the vegetation period of rice crop were analysed to obtain the entropy, anisotropy and alpha angle. The relationship between the Sentinel–1polarimetric decomposition parameters and the in–situ measured biophysical parameters of rice crop for various phenological stages was studied first time for the study area.

MATERIAL AND METHODS

Study area

Rice growing regions of Anand (central co-ordinates 22.57°N, 72.93°E) and Kheda (central co-ordinates 22.75°N, 72.68°E) districts in the middle Gujarat Agroclimatic Zone-III of Gujarat state in India was selected as the study area (Fig. 1). In this region, the major crop in the monsoon (*Kharif*) season is rice followed by pearl- millet, cotton and horticultural crops while in the winter (*Rabi*) season wheat and tobacco are the major crops.

Satellite data

The study was carried out using C–band Sentinel–1A dual polarization (VH and VV) single look complex (SLC) data acquired in Interferometric Wide (IW) swath mode in descending direction with incidence angle between 30.81° near range and 46.29° far range at 5.405 GHz radar frequency. The satellite data was downloaded from ESA Copernicus Open Hub (https://scihub.copernicus.eu/). Satellite data on four acquisition dates from August 2018 to October 2018 were considered for analysis since it covered the major phenological stages of rice.

Field data

The life cycle of the rice crop lasts around 130–160 days from germination to maturity depending on the variety. In this region, the sowing dates of paddy depend on the irrigation facility available for the fields and varied from field to field within the study area. The field surveys were conducted such that various Biologische Bundesanstalt, Bundessortenamt, and CHemicalindustry (BBCH) scale (Meier *et al.,* 2009) phenological growth stages could be recorded. The typical appearance of the crop observed at various phenological growth stages is shown in Fig. 2. Field data were collected between August 2018 to October 2018 synchronous to satellite pass dates over the study area to monitor the biophysical parameters through the different phenological growth stages of the crop. Table 1 lists the dates of field surveys, the BBCH scale growth stages observed and Sentinel–1 acquisition date. The minimum field size chosen for the study was ~100 m^2 while the minimum distance between two fields was ~800 m. Hand–held GPS instrument (Garmin 64S) with 3.65 m accuracy was used to note the latitude and longitude of the crop fields. Crop parameters such as fresh biomass (g m^{-2}), dry biomass (g m^{-2}), VWC (g m^{-2}), plant height (cm), plant–plant and row–row distance (cm), crop age (DAS), crop cover (%), crop vigour and soil parameters like soil type, soil moisture (%), soil roughness (cm) were recorded during field visits. Fresh and dry biomass was obtained by weighing the plant in a weighing balance machine with 0.1 g accuracy. For measurement of dry biomass, the

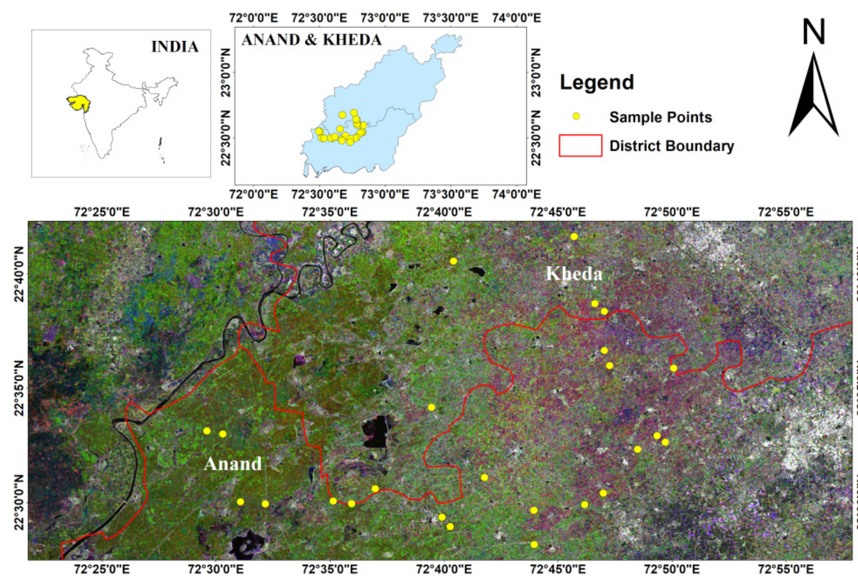

Fig.1: The study area map showing the RGB composite of (Red- VH 12 August 2018, Green-VH 17 September 2018, Blue- VH 11 October 2018).

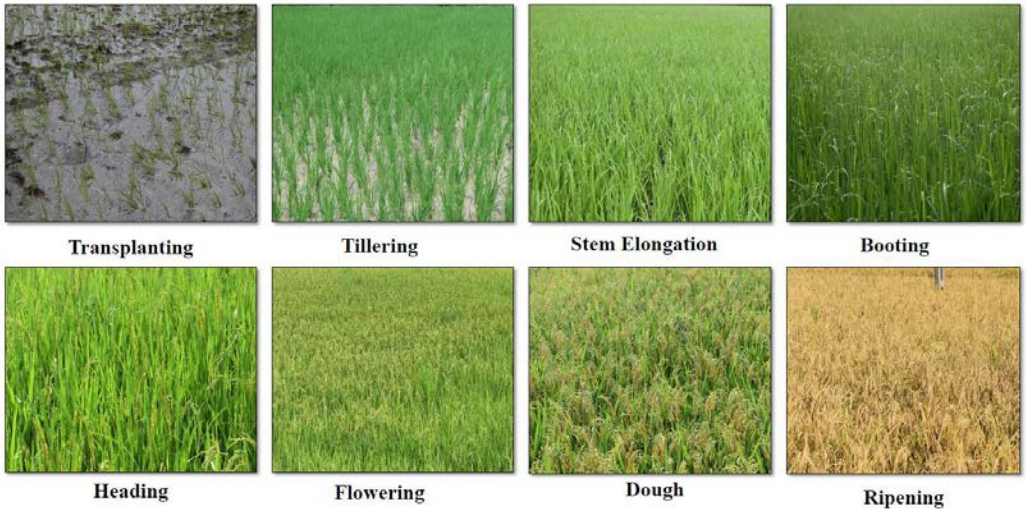

Fig. 2: Field survey photographs from August 2018 to October 2018 for various crop growth stages.

Table 1: Field survey and Sentinel–1 acquisition dates with BBCH growth stages

Field surveys	Sentinel–1 acquisition dates	BBCH growth stages
10–Aug. to 12–Aug.	12–Aug.–2018	BBCH 21-49 (Tillering – End Booting)
16–Sept. to 17–Sept.	17–Sept.–2018	BBCH 51-77 (Heading – Late Milk)
10–Oct. to 11–Oct.	11–Oct.–2018	BBCH 51-77(Heading – Late Milk), BBCH 83-92 (Ripening)
23–Oct.	23–Oct.–2018	BBCH 83-92 (Ripening)

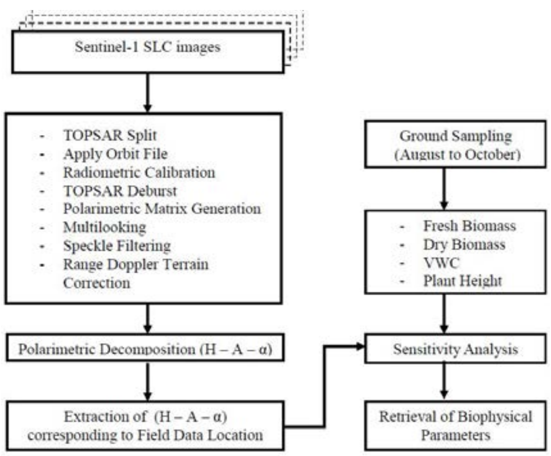

Fig. 3: Methodology flow chart adopted in the study.

plant was oven dried at 60 °C for 24 hours before weighing. VWC was obtained by subtracting the dry biomass from fresh biomass weight.

Methodology

The methodology followed for this study can be divided into two categories. First, the polarimetric decomposition parameters *viz.* entropy (H), anisotropy (A) and alpha angle () were extracted from the multi-temporal dataset of Sentinel–1. The details about the data analysis procedures are depicted in Fig. 3.

Extraction of Sentinel–1 polarimetric decomposition parameters

The eigenvector and eigenvalue-based H-A-α decomposition by Cloude and Pottier (1997) with its modification for dual-polarimetric data (Cloude, 2007; Ji and Wu, 2015) was followed to obtain entropy, anisotropy and alpha angle. In this method, the eigenvalues and the eigenvector of the coherency matrix [T] or covariance matrix [C] are used to calculate the decomposition parameters (Lee and Ainsworth 2010). For dual-polarimetric case the decomposition parameters are defined as:

$$H = \sum_{i=1}^{2}(-P_i log_2 P_i) \qquad (1)$$

$$A = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} \qquad (2)$$

$$\alpha = \sum_{i=1}^{2} P_i \alpha_i \qquad (3)$$

where,

$$P_i = \frac{\lambda_i}{\sum_{j=1}^{2} \lambda_j} \qquad (4)$$

$$\alpha_i = cos^{-1}(|u_{1i}|) \qquad (5)$$

λ are the eigenvalues and are the eigenvectors.

The multi-temporal Sentinel–1 SLC datasets were processed using the Sentinel Application Platform (SNAP) to obtain the polarimetric decomposition parameters. The steps followed for the processing of data is shown in the Fig. 3. The resulting images had a resolution of 10 × 10 m and contained the H, A and α values which were extracted corresponding to the location of field data collection for each acquisition dates.

Statistical analysis

Pearson Correlation between crop biophysical parameters and polarimetric decomposition parameters for various dataset has been performed with t test to check the significance. Regression analysis was done to quantify the capacity of the Sentinel–1polarimetric decomposition parameters in monitoring the crop biophysical parameters. The linear model calculates the best correlation between the crop biophysical parameters and the polarimetric decomposition parameters using a linear equation (Eq. (6)).

Polarimetric Decomposition Parameter

$$=m \times (\text{Biophysical parameter})+c \quad (6)$$

where, m and c are model parameters that are evaluated by least square fitting.

In the logarithmic model, the best correlation between the natural logarithm of the crop biophysical parameters and the polarimetric decomposition parameters was evaluated following Eq. (7).

Polarimetric Decomposition Parameter

$$=a \times \ln(\text{Biophysical parameter})+b \quad (7)$$

where, a and b are model parameters that are evaluated by least square fitting.

Additionally, multiple regressions for both the models using not only the polarimetric decomposition parameters but also the VH and VV backscatter coefficients were done (Eq. (8) and (9)).

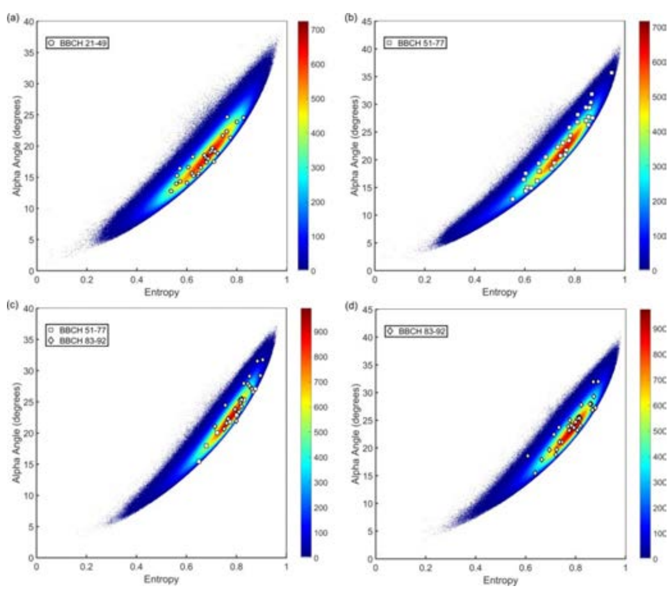

Fig. 4: H– plane for the study area on different Sentinel–1 acquisition dates. (a) 12 August (b) 17 September (c) 11 October and (d) 23 October. The white points are the H– values.

Biophysical parameter

$$=m_1 \times VH + m_2 \times VV + m_3 \times H + m_4 \times A + m_5 \times \alpha + C \quad (8)$$

where, m_i (i = 1 to 5) and C are model parameters that are evaluated by least square fitting.

In (Biophysical parameter)

$$=a_1 \times VH + a_2 \times VV + a_3 \times H + a_4 \times A + a_5 \times \alpha + B \quad (9)$$

where, a_i (i = 1 to 5) and B are model parameters that are evaluated by least square fitting.

The regression analysis was done for the entire temporal dataset and for group of BBCH growth stages separately. Finally, various crop biophysical parameters were predicted considering the model that yielded the best BBCH stage-wise correlation for the multiple regression analysis. The values thus obtained were compared with the actual biophysical parameter values recorded during the field surveys.

RESULTS AND DISCUSSION

The polarimetric decomposition parameters are governed by the structure of the plants as well as the contribution to the radar signal from soil surface scattering and scattering from vegetation. During the vegetation period as the plant evolves, the contribution from volume scattering from vegetation and that from soil surface scattering to the signal keeps on varying. Cloude and Pottier (1997) developed a method where the basic scattering mechanisms could be visualized in a H– plane by dividing the plane into nine zones each representing a scattering mechanism. Fig. 4 shows the H– plane for the study area on the Sentinel–1 acquisition dates along with the H– values for the field locations considered for the study. No discrimination could be made between the scattering mechanisms throughout the vegetation period (Ji and Wu, 2015) that showed that for dual-polarimetric data, such as Sentinel–1 with VH-VV polarization, H– plane-based discrimination of scattering mechanism is extremely poor.

The relationship of biophysical parameters with Sentinel-1A SAR parameters is correlated at different growth stages using Pearson correlation coefficient. It was noticed that, with the use of Pearson correlation coefficient at different growth stages the response of each polarimetric decomposition parameter was different with rice crop biophysical parameters.

Table 2 shows that the crop biophysical parameters exhibit poor correlation when entire growth cycle is considered. The impact of the crop biophysical parameters on radar backscatter signal is evident when the crop growth is divided in BBCH scale. It is noticeable from the results that BBCH 21-49 yields better correlation when there is sparse canopy cover and radar signals can better interact with the entire canopy structure. All the results obtained are extremely significant with $p< 0.001$.

Table 2: Pearson correlation coefficient (R) between crop biophysical parameters and polarimetric decomposition parameters

Crop biophysical parameter	Dataset	VH	VV	Entropy	Anisotropy	Alpha
Fresh biomass (g m^{-2})	Entire Dataset	0.076***	-0.144***	0.390***	-0.377***	0.355***
	BBCH 21-49	0.795***	0.449***	0.750***	-0.719***	0.707***
	BBCH 51-77	0.015***	0.219***	-0.144***	0.094***	-0.131***
	BBCH 83-92	-0.719***	-0.452***	-0.348***	0.327***	-0.407***
Dry biomass (g m^{-2})	Entire Dataset	-0.006***	-0.177***	0.326***	-0.307***	0.282***
	BBCH 21-49	0.464***	0.295***	0.343***	-0.325***	0.384***
	BBCH 51-77	0.091***	0.320***	-0.130***	0.109***	-0.154***
	BBCH 83-92	-0.644***	-0.378***	-0.341***	0.321***	-0.381***
VWC (g m^{-2})	Entire Dataset	0.114***	-0.103***	0.374***	-0.366***	0.343***
	BBCH 21-49	0.799***	0.444***	0.773***	-0.741***	0.715***
	BBCH 51-77	-0.029***	0.133***	-0.134***	0.074***	-0.101***
	BBCH 83-92	-0.555***	-0.332***	-0.322***	0.304***	-0.403***
Plant height (cm)	Entire Dataset	0.430***	0.071***	0.552***	-0.520***	0.491***
	BBCH 21-49	0.824***	0.672***	0.728***	-0.704***	0.682***
	BBCH 51-77	0.451***	0.377***	-0.114***	0.088***	-0.186***
	BBCH 83-92	-0.388***	-0.226***	-0.168***	0.148***	-0.144***

***p<0.001, Number of data points n=97 (Entire dataset), n=25 (BBCH 21-49), n=29 (BBCH 51-77), n=43 (*BBCH 83-92)*

Table 3: R^2 values of the regression between crop biophysical parameters and polarimetric decomposition parameters for entire temporal dataset.

All crop stages	Model	Entropy	Anisotropy	Alpha
Fresh biomass (g m^{-2})	lin	0.147	0.137	0.121
	log	0.265	0.241	0.23
Dry biomass (g m^{-2})	lin	0.126	0.114	0.102
	log	0.249	0.228	0.223
VWC (g m^{-2})	lin	0.134	0.127	0.111
	log	0.262	0.237	0.224
Plant height (cm)	lin	0.303	0.268	0.239
	log	0.325	0.282	0.253

Apart from Pearson correlation, both linear and logarithmic regression models were applied to correlate the crop biophysical parameters to H-A- derived from the corresponding Sentinel–1 images. The R^2 values obtained from the regression analysis are listed in Table 3. The correlation between the observed crop biophysical parameters and the polarimetric decomposition parameters is poor or very moderate when the entire temporal dataset is considered for regression analysis. The highest R^2 value (0.325) is obtained for logarithmic regression between plant height and entropy. Since scattering mechanisms are affected by the changes in structure and appearance that the plants undergo during various growth stages, considering the entire vegetation period for regression analysis yields a poor result which was observed in earlier study as well (Harfenmeister *et al.,* 2021). To obtain a meaningful correlation, regression analysis was performed on broad BBCH growth stages.

During the field surveys conducted from 10th to 12th August the crop was observed to be in the tillering (BBCH 21) to booting (BBCH 49) stage. Table 4 lists the R^2 values obtained from regression analysis of BBCH 21-49 growth stage. The BBCH 21-49 crop growth stage gives the best correlation between the polarimetric decomposition parameters and all the crop biophysical parameters. The reason for this may be the fact that, at this stage the C-band SAR signal can interact with the full length of the crop. Better correlations at this growth stage have been also observed in earlier studies for regression with various SAR parameters (Harfenmeister *et al.,* 2021; Kushwaha *et al*., 2022).

Regression with polarimetric decomposition parameters is not as good as that with VH backscatter coefficient for all crop parameters. The best R^2 value (0.6) is obtained for correlation of entropy with VWC in the linear model. Anisotropy and alpha angle also have the best R^2 values for correlation with VWC in the linear model (0.55 and 0.512 respectively). Multiple regressions using all the SAR parameters give a better correlation than that of individual parameters. Multiple regression with linear model for VWC yields the best R^2 value (0.765).

The second group of dataset considered was for crop between heading growth stage (BBCH 51) to late milk stage (BBCH 77). The crop biophysical parameters have a high value range in the BBCH 51-77 stage and there are no major structural changes in the plant from beginning of the heading stage. The regression analysis reveals that there is negligible or no correlation between the crop biophysical parameters and the polarimetric decomposition parameters for this stage (Table 5). Multiple regression yields the best R^2 values, but they are low. Similar behaviour has been also observed for regression with the backscatter parameters for rice (Kushwaha *et al*., 2022).

The last group of dataset considered for the regression analysis was the BBCH 83-92 stage (ripening stage). Better R^2 values were obtained for regression at this stage as compared to the BBCH 51-77 stage (Table 6). Although there is some improvement, as

Table 4: R^2 values of the regression between crop biophysical parameters and polarimetric decomposition parameters for BBCH 21-49 crop stages.

BBCH 21-49	Model	VH	VV	Entropy	Anisotropy	Alpha	Multi
Fresh biomass (g m^{-2})	lin	0.632	0.201	0.563	0.517	0.499	0.748
	log	0.641	0.216	0.553	0.501	0.421	0.757
Dry biomass (g m^{-2})	lin	0.215	0.09	0.118	0.106	0.148	0.275
	log	0.256	0.11	0.138	0.122	0.134	0.287
VWC (g m^{-2})	lin	0.64	0.2	0.6	0.55	0.512	0.765
	log	0.63	0.21	0.566	0.513	0.418	0.76
Plant height (cm)	lin	0.68	0.45	0.529	0.495	0.465	0.735
	log	0.673	0.434	0.55	0.507	0.486	0.759

Table 5: R^2 values of the regression between crop biophysical parameters and polarimetric decomposition parameters for BBCH 51-77 crop stages.

BBCH 51-77	Model	VH	VV	Entropy	Anisotropy	Alpha	Multi
Fresh biomass (g m^{-2})	lin	0.004	0.042	0.024	0.012	0.022	0.2
	log	0.003	0.043	0.032	0.018	0.026	0.196
Dry biomass (g m^{-2})	lin	0.002	0.103	0.02	0.015	0.028	0.157
	log	0.001	0.102	0.024	0.016	0.03	0.193
VWC (g m^{-2})	lin	0.013	0.014	0.02	0.008	0.014	0.209
	log	0.012	0.017	0.036	0.019	0.026	0.194
Plant height (cm)	lin	0.127	0.131	0.014	0.008	0.037	0.337
	log	0.123	0.137	0.018	0.012	0.042	0.336

Table 6: R^2 values of the regression between crop biophysical parameters and polarimetric decomposition parameters for BBCH 83-92 crop stages.

BBCH 83-92	Model	VH	VV	Entropy	Anisotropy	Alpha	Multi
Fresh biomass (g m^{-2})	lin	0.52	0.204	0.121	0.107	0.166	0.575
	log	0.471	0.178	0.118	0.104	0.162	0.529
Dry biomass (g m^{-2})	lin	0.414	0.178	0.064	0.056	0.072	0.421
	log	0.38	0.16	0.075	0.067	0.087	0.39
VWC (g m^{-2})	lin	0.31	0.11	0.104	0.092	0.163	0.408
	log	0.337	0.125	0.104	0.092	0.163	0.435
Plant height (cm)	lin	0.15	0.05	0.028	0.022	0.021	0.169
	log	0.15	0.05	0.022	0.017	0.016	0.168

indicated by the R^2 values, the correlation between the polarimetric decomposition parameters and the crop biophysical parameters is still very poor. The best R^2 values are obtained for multiple regressions using all the SAR parameters but it is dominated by the contribution from VH backscatter coefficient and polarimetric decomposition parameters does not have a major role. Fig. 5 shows the correlated scatter plots of the various crop biophysical parameters and the polarimetric decomposition parameters along with the fitted regression curve from both the models.

For each broad BBCH stages, the crop biophysical parameters were retrieved as a function of the SAR parameters following the multiple regression models i.e, either equations 8 or 9, that yield the best correlations. To evaluate the accuracy of the regression model, the observed and retrieved crop biophysical parameters were compared on a 1:1 plot which is shown in Fig. 6. A RMSE value of 675 g m^{-2} is obtained for fresh biomass, while for dry biomass it is 356 g m^{-2}. For VWC and plant height the RMSE values are 487 g m^{-2} and 9.4 cm respectively. All the retrieved crop biophysical parameters yield a lower RMSE when polarimetric decomposition parameters are also considered in the multiple regressions. This indicates that polarimetric decomposition parameters have a role to play in monitoring the crop biophysical parameters of rice crop along with the backscattering parameters.

CONCLUSION

The variability in scattering mechanisms of SAR

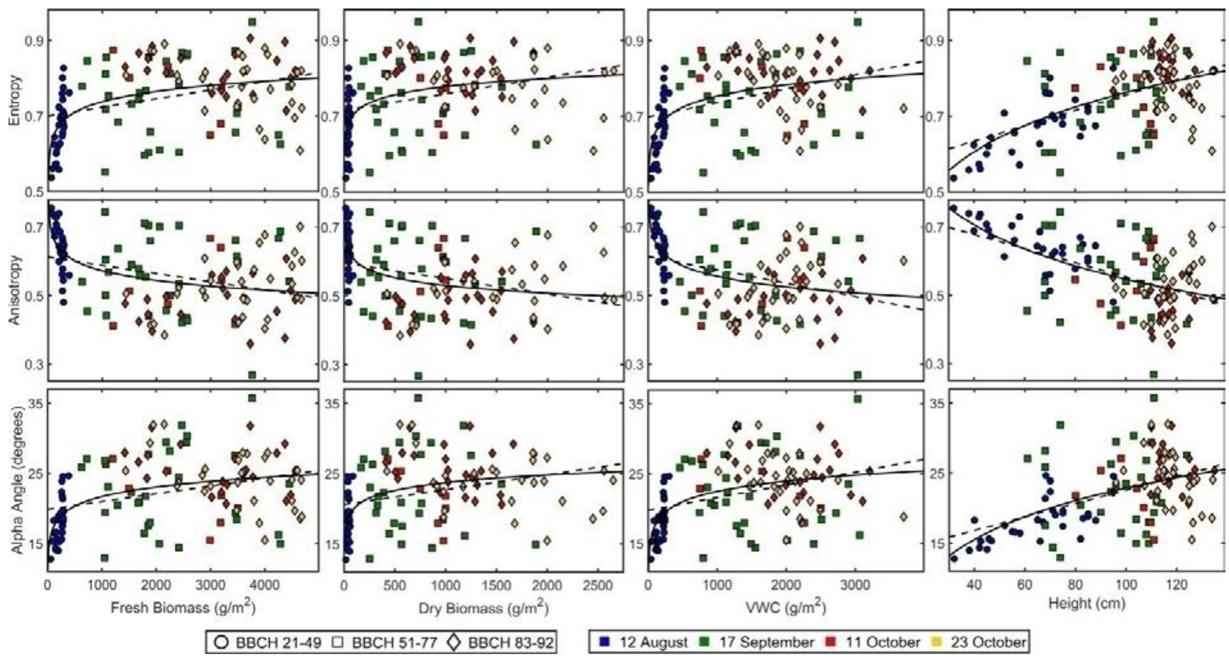

Fig. 5: Correlated scatter plots of the various crop biophysical parameters for the entire temporal data. The solid line is the logarithmic fit and dashed line is the linear fit to the data as obtained by regression analysis.

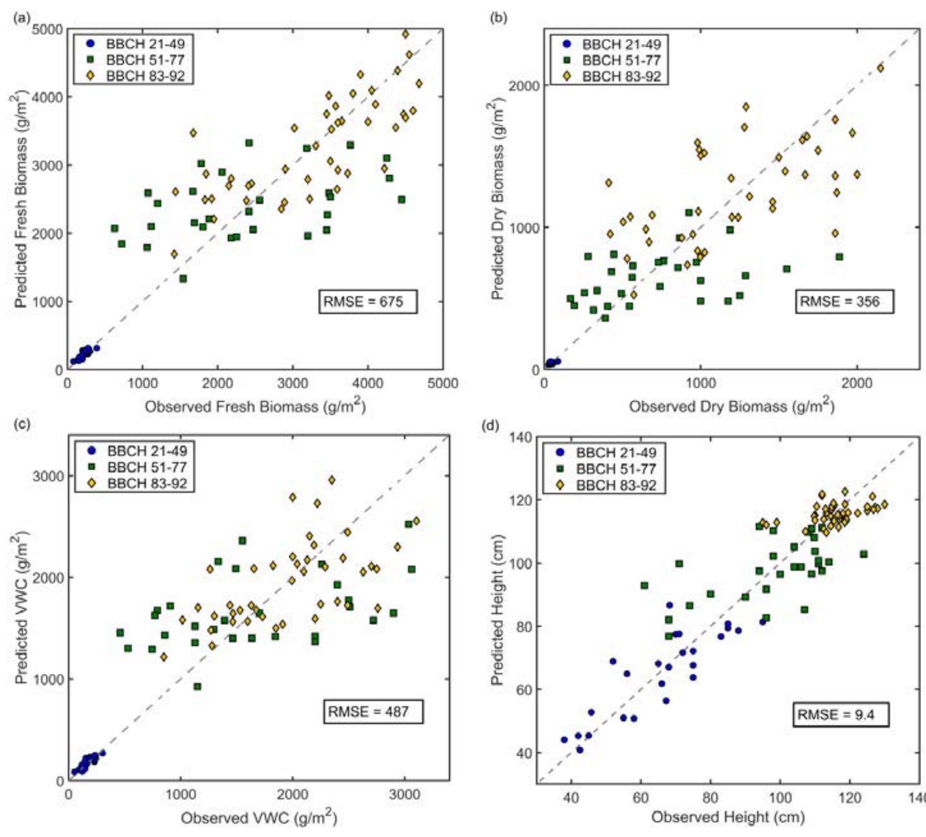

Fig. 6: Observed versus predicted crop biophysical parameters (a) Fresh biomass, (b) Dry biomass, (c) VWC and (d) Plant height. The dashed line is the 1:1 plot.

signals during the vegetation period could not be monitored with the H– plane analysis. This can be attributed to the lack of required combination of co-polarization (*i.e.* HH–VV) essential for extracting the scattering mechanisms in the Sentinel–1 data which is VH–VV polarized. The regression analysis using linear and logarithmic models show that the best correlations are obtained when the crop is in the early phenological stages *i.e.* from tillering until end of booting (BBCH 21-49 stage). Multiple regression using

VH and VV backscatter coefficients, entropy, anisotropy and alpha angle resulted in better R^2 values as compared to using backscatter coefficients alone confirming the potential utility of the polarimetric decomposition parameters as an additional input for crop monitoring along with the backscatter parameters. Also, the results reported here for the sensitivity of crop biophysical parameters to dual-polarimetric decomposition parameters can be examined for the full-polarmetric SAR data for the better understanding of its behaviour throughout the crop cycle.

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