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Integration of Sentinel-1A SAR data with CERES-RICE model for predicting rice yield in Udham Singh Nagar, Uttarakhand

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सार – इस अध्ययन में उत्तराखंड के उधम सिंह नगर जिले में चावल की उपज के मानचित्रण और अनुमान के लिए चावल फसल मॉडल के साथ बहु-कालिक और बहु-ध्रुवीकृत सेंटिनल-1 ए सिंथेटिक एपर्चर रेडार (एसएआर) डेटा को आमेलन करने की उपयोगिता पर चर्चा की गई है। CERES RICE मॉडल, जो DSSAT-4.7 में अंत:स्थापित है, को एक आमेलन विधि का उपयोग करके फिर से शुरू किया गया था जिसमें कालिक एकल ध्रुवीकृत चावल पश्च प्रकीर्णन गुणांक को जिले के लिए प्रत्येक चावल पिक्सेल के लिए समूहीकृत किया गया था, और फिर जिले में चावल वितरण के बारे में सपोर्ट वेक्टर वर्गीकरण का उपयोग करके सेंटिनल-1ए एसएआर छवियों से चावल के खेतों की मैपिंग करके जानकारी प्राप्त की गई। मॉडल के पुन: आरंभीकरण के दौरान आमेलन प्रक्रिया के साथ वांछनीय इनपुट पैरामीटर सेंटिनल-1ए एसएआर छवियों से प्राप्त चावल पश्च प्रकीर्णन गुणांक और युग्मित मॉडल से प्राप्त चावल पश्च प्रकीर्णन गुणांक के बीच एक अच्छे कालिक समझौते की अनुमति देते हैं। अर्ध अनुभवजन्य चावल बैकस्कैटर मॉडल के साथ CERES RICE मॉडल का एकीकरण लीफ एरिया इंडेक्स (LAI) का उपयोग करके हासिल किया गया, जो चावल बैक स्कैटरिंग गुणांक को अनुकरण करने के लिए एक आवश्यक लिंक के रूप में कार्य करता है। पुन: आरंभीकरण के बाद, प्रत्येक चावल पिक्सेल से चावल की उपज की गणना की गई और अनुसंधान के क्षेत्र का उपज मानचित्र विकसित किया गया। परिणामों से पता चला कि युग्मित मॉडल ने3190 किलोग्राम/हेक्टेयर चावल की उपज का अनुमान दिया, जो पांच साल की औसत जिले की उपज के काफी करीब था, जो कि 3160 किलोग्राम/हेक्टेयर था, जिसमें युग्मित और जिले की पांच साल की औसत चावल उपज के बीच 30 किलोग्राम/हेक्टेयर का अंतर था। प्राप्त परिणामों के आधार पर, यह अनुमान लगाना संभव है कि सेंटिनल-1ए एसएआर डेटा में चावल की फसल की उपज का आकलन करने की क्षमता के साथ, चावल की निगरानी और मानचित्रण की काफी संभावनाएं हैं। उपज काअनुमान एक महत्वपूर्ण कदम है जिसका उपयोग चावल की उपज और उत्पादन का मौसमी आकलन प्रदान करके किसानों और नीति निर्माताओं की सहायता के लिए किया जा सकता है। इस जानकारी का उपयोग संसाधनों की बेहतर योजना के लिए किया जा सकता है।

ABSTRACT. The utility of assimilation of multi-temporal and multi-polarized Sentinel-1A Synthetic Aperture Radar (SAR) data with a rice crop model for mapping and estimating rice yield in the Udham Singh Nagar district of Uttarakhand has been discussed in this study. The CERES RICE model, which is embedded in DSSAT- 4.7, was re-initialized using an assimilation method in which the temporal single polarized rice backscattering coefficients were grouped for each rice pixel for the district, and then information about rice distribution over the district was obtained by mapping rice fields from Sentinel-1A SAR images using support vector classification. The desirable input parameters with the assimilation procedure during re-initialization of the model allow a good temporal agreement between the rice backscattering coefficients derived from Sentinel-1A SAR images and the rice backscattering coefficient derived from the coupled model. The integration of the CERES RICE model with the semi empirical rice backscatter model was achieved using Leaf Area Index (LAI), which acts as an essential link to simulate the rice back scattering coefficients. After re-initialization, the yield of rice was calculated from each rice pixel and a yield map of the field of research was developed. The results showed that the coupled model gave an estimate of rice yield of 3190 kg/ha, which was quite near to the five-year average district yield, which was 3160 kg/ha, with 30 kg/ha difference between the coupled and the five-year average rice yield of the district. Based on the obtained results, it is possible to infer that Sentinel-1A SAR data has great potential for monitoring and mapping of rice, with the ability to predict the rice crop yield. The prediction of yield is an important step that may be utilized to assist farmers and policymakers by providing in-season estimates of rice yield and production. This information could be used for better planning of the resources.

Key words – Ceres rice, DSSAT, LAI, SAR, Sentinel-1A, Yield.

1. Introduction

Rice yield prediction is a primary objective of rice monitoring. Total estimates regarding the rice planted areas and productivity are generally based on ground survey information. This process is very time-consuming and expensive. In the early 1980s, the whole world gave more attention towards optical remote sensing for estimation of crop yield. Significant achievements were achieved after many studies were carried out (Li *et al*., 2003). Setiyono *et al*. (2018) utilized multi-temporal C-band Sentinel-1A SAR imagery and to classify rice crop in multiple locations in Tropical Asia and incorporate the information into ORYZA Crop Growth Simulation model (CGSM) which generated high resolution yield maps. Similarly, for estimating the yield of winter Wheat for the North China region, (Son *et al*., 2016) integrated LAI derived from MODIS data with crop simulation model (DSSAT) for rice yield estimation in Taiwan. The shortcoming of optically acquired remote sensing data is that it is lost during overcast weather or during the rainy season, making real-time crop growth monitoring and precise rice yield estimation very challenging. Radar data is an ideal choice since it is the best data source for agricultural monitoring and yield prediction across wide areas in tropical and subtropical countries, particularly during the *kharif* season (Ribbes and Toan, 1999; Li *et al*., 2003; Chen *et al*., 2006). Crop simulation models (CSM) are being extensively integrated with remote sensing and GIS frameworks across the world, which shows a very high rate of success in field applications such as crop growth monitoring. The integration requires re-initialization process which helps in combining the two models through a link. In this study, Sentinel-1A SAR data is used, which was launched by the European Space Agency in the year 2014. This satellite is configured with a C-SAR payload having a frequency of 5.404 GHz, which gives dual polarized data in the form of VV and VH polarizations. The swath of this satellite is 250 km with a spatial resolution of 5×20 meters. The crop growth simulation model that has been used in this study is CERES RICE. This model is embedded in DSSAT- 4.7. DSSAT (Decision Support System for Agrotechnology Transfer) is application software that uses crop simulation models to simulate 42 crops. CERES stands for crop environment resource synthesis, which is utilized as a tool for designing crop management activities. The integrated system can be used for assessing the local variability, seasonal weather factors and crop management signals. Remote Sensing (RS) data, acquired continuously over agricultural land, helps in the identification and mapping of crops and also in assessing crop vitality. The remotely sensed data can give information related to crop environment, leaf area index, crop distribution, and crop phenology. The main factors on which productivity and growth of crops depend are mainly weather, soil and management variables, which change considerably across space. Dadhwal (2005) used the above information into crop simulation models in various ways, such as for recalibrating particular parameters, for direct forcing of variables or differences in simulation-observation to correct yield estimates. The present study aims at development of spectral model for analyzing rice growth and yield attributes by taking plant observations during satellite pass and thereafter applying the spectral model at the district level for yield prediction by integrating Sentinel 1-A satellite Synthetic aperture radar data with the DSSAT (CERES- RICE) model.

TABLE 1

Geographical location of the study sites

S. No.	Site	Latitude	Longitude
1.	Sainik farm 1	29° 2' 6.59" N	79° 25' 13.50" E
2.	Sainik farm 2	29° 2' 3.18" N	79° 25' 18.17" E
3.	PCP	29° 0' 55.65" N	79° 29' 25.64" E
4.	Beni	29° 1' 1.80" N	79° 30' 4.78" E
5.	Near Fisheries College	29° 1' 11.50" N	79° 30' 20.80" E

2. Materials and methods

2.1. *Study area and data description*

The study area was Udham Singh Nagar district which is located in the *Terai* region, of Uttarakhand state. It extends from 28° 53' to 29° 23' N latitudes and 78° 45' to 80° 08' E longitudes. This district of Uttarkhand state is the leading producer of rice and wheat. The prominent cropping system in this area is Rice-Wheat due to this the investigation was done at five different locations namely Sainik farm 1 and 2, PCP, Beni and Near Fisheries College over the campus of GBPUAT, as shown in Table 1.

The ground truth observations were taken at an interval of 12 days from July 25 to October 10. There were four observations, *viz*., growth stages of rice, density of plants in the field, height of the plants, and general information related to field management, which was taken from a plot size of 1 m^2. By taking 5 samples at random within a plot, the above ground biomass of stems, (green + dead) leaves and ears were quantified individually. Ceptometer LP-80 was used to assess LAI over the course of the study. At the time of rice harvesting, information on actual rice production in the district was gathered.

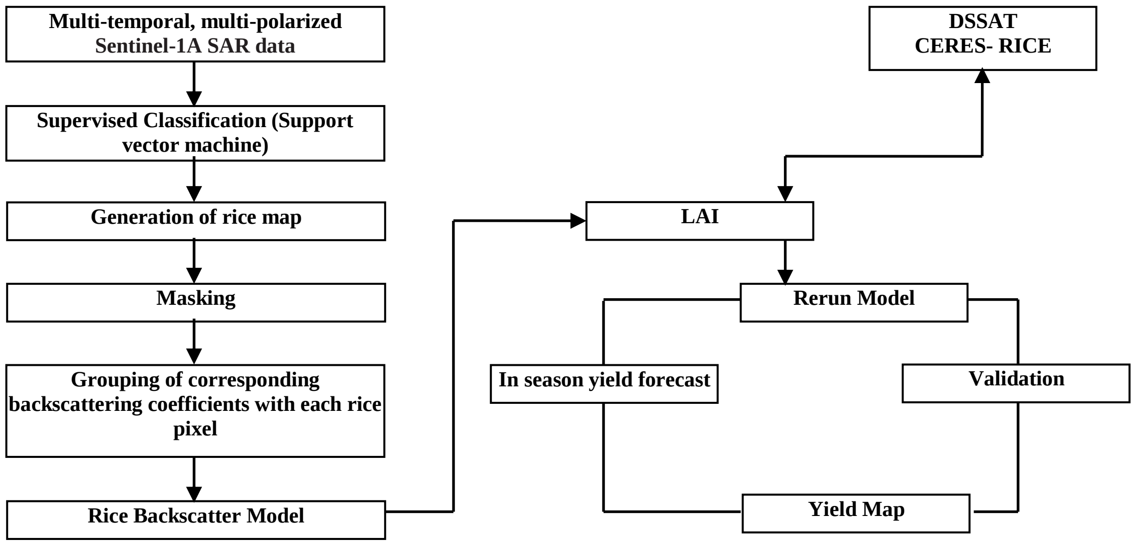

Fig. 1. Rice yield mapping scheme based on Senitnel-1A SAR data and DSSAT CERES-RICE

TABLE 2

Impression of Sentinel-1A SAR images and rice growth stages at each acquisition date

Date of Acquisition	Polarization	Pass	Spatial resolution	Incidence angle	Rice Growth stage
25-26 Jul, 2017	VV/VH	Descending	5 × 20 m	29.1° to 46.0°	Early stage
18-19 Aug, 2017	VV/VH	Descending	5 × 20 m	29.1° to 46.0°	Mid stage
11-12 Sep, 2017	VV/VH	Descending	5 × 20 m	29.1° to 46.0°	Reproductive/Grain filling stage

The daily weather data that were used in the study were acquired for the year 2017 from the Agrometeorological observatory located at Crop Research Centre, G. B. Pant University of Agriculture and Technology. The quantity of insolation available at Pantnagar was estimated using weather data such as temperature (maximum and minimum), rainfall and Bright Sunshine Hours (BSS). Three Sentinel-1A SAR products were used to monitor the rice season in 2017, as indicated in the Table 2.

2.2. *The rice yield mapping system based on Senitnel-1A SAR data and DSSAT (CERES-RICE)*

The complete mapping of rice yield using SAR data procedure was broken into two phases. The first phase involved creating a rice distribution map of Udham Singh Nagar district using a mapping method and employing Sentinel-1A SAR data. The mapping was done by using the SVM (Support Vector Machine) supervised classification technique which identify the class associated with each pixel. From complex and noisy data SVM derives satisfying classification results. SVM is a supervised classification system which is based on statistical learning theory it basically separates the classes by making a decision surface which maximizes the margin between the classes. This surface is called as optimal hyper plane and the points which are very closest to the hyper plane are called as support vectors these support vectors are main elements of the training set. The mapping tool which was used in this study is ENVI - 4.8 (Environment for Visualising Images). The rice map created by mapping was used to mask the Sentinel - 1A SAR images in order to identify the rice fields and get the backscattering coefficients. The backscattering coefficients which correspond to each rice pixel in the rice map have been grouped for each polarization.

The implementation of an assimilation approach to estimate the rice yield for each rice pixel is the second phase of this study. The observed rice backscattering coefficients were utilized to re-initialize the crop growth simulation model CERES - RICE using the assimilation

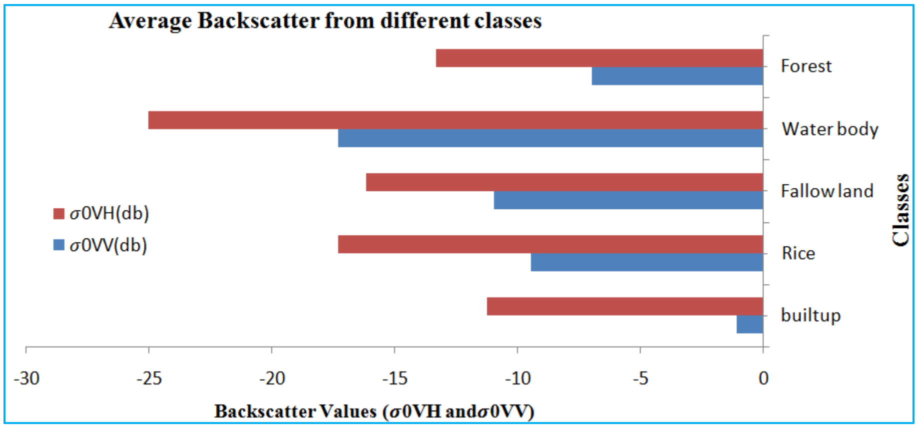

Fig. 2. Backscatter statistics of different land cover classes

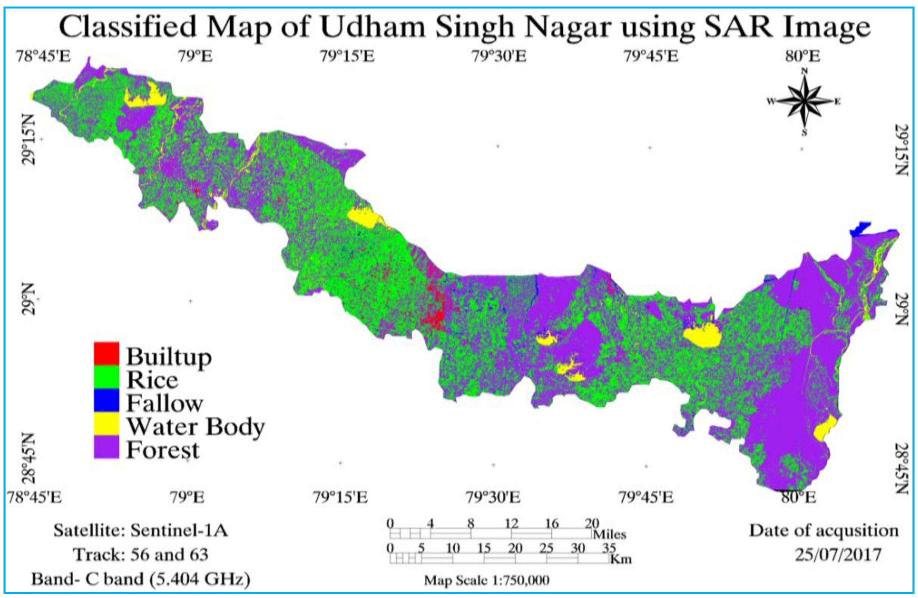

Fig. 3. Classified image of Udham Singh Nagar district

method (Bouman *et al*., 2001). The CERES-RICE model was merged with the rice backscatter model during assimilation, with LAI serving as a crucial connection to simulate rice backscattering coefficients. The assimilation method re-initializes the model with appropriate input parameters, allowing for a promising temporal link between the observed and simulated rice backscattering coefficients. After the re-initialization process was completed, the rice yield map of Udham Singh Nagar district was created by computing the crop yield associated with each rice pixel in the CERES-RICE model. The most significant stage in SAR image processing is calibration, which is performed by a calibration operator provided by the European Space Agency (ESA) in Sentinel's Application Platform (SNAP) to extract backscattering values of the relevant pixels. The refined Lee speckle filter, which is based on lowest mean square error, was employed to reduce the speckle noise. The terrain was then corrected using a Range Doppler Terrain Correction method provided in ESA’s SNAP. The scheme of rice yield mapping and its integration with CERES RICE model is illustrated in Fig. 1, the technique of integrating Sentinel-1A SAR data with the crop simulation model for rice yield prediction is based on multi-temporal and multi-polarized Sentinel-1A SAR data. The input files which are required for running the model were weather file, soil file and management file. The weather file was constructed by integrating several meteorological parameters such as temperature (maximum and minimum), precipitation and solar radiation. The soil

TABLE 3

Genotype coefficients of five different rice cultivars

Symbol	Description	Genetic Coefficients of varieties				
		HKR-47	PR-121	Pant-4	HKR-47	HKR- 47
P1	Time period (expressed as growing degree days [GDD] in °C above a base temperature of 9 °C) from seedling emergence to the end of juvenile phase during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as the basic vegetative phase of the plant	1150	850	880	1150	1150
P2R	Extent to which phasic development leads to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P2O	50	20	45	50	50
P2O	Critical photoperiod or longest day length (in hours) at which the development occurs at maximum rate. At values higher than P2O the development rate is slowed (depending on P2R), there is delay due to longer day length	11.4	12.1	11.4	11.4	11.4
P5	Time period in GDD in °C from beginning of grain-filling (3 - 4 days after flowering) to physiological maturity with a base temperature of 9 °C	300	550	450	300	300
G1	Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes at heading. A typical value is 55	40	50	40	40	40
G2	Single dry grain weight (g) under ideal growing conditions, *i.e*., non limiting light, water, nutrients, and absence of pests and diseases	0.025	0.028	0.01	0.025	0.025
G3	Tillering coefficient (scalar value) relative to IR64 cultivars under ideal conditions. A higher tillering cultivar would have coefficient greater than 1	2	0.5	2	2	2
G4	Temperature tolerance coefficient. Usually 1.0 for cultivars grown in normal environment.G4 for japonica type rice grown in warmer environments would be 1.0. Tropical rice grown in cooler environments or season will have G4 < 1.0	1	1	0.8	1	1
PHINT	Phyllochron interval	70	83	83	70	70

file includes the information related to soil structure, texture, bulk density, upper drained limit, lower drained limit, mineral, nitrogen, pH, EC, organic carbon, and other data which were gathered from published literature to generate the soil file. Actual information from the representative fields like cultivar, planting dates, harvesting dates, irrigation information, and fertilizer dosage were used to construct the management file. To find out the degree of coincidence between the observed yield and the simulated coupled yield, the Root Mean Square Error (RMSE) method was used so that the statistical evaluation and validation of the outcomes could be done.

3. Results and discussion

There were two phases adopted for the integration of Sentinel-1A SAR data into the rice growth simulation model. The initial phase in estimating rice yield was achieved through image classification and rice area estimation. The rice map of the zone of study has been derived in our previous study using the support vector machine method classification (Bhatt *et al*., 2018), with a rice mapping accuracy of 92.88%. The backscatter statistics of different land cover classes showing average backscatter for VH (σ0VH) and VV (σ0VV) polarisation as shown in Fig. 2, with a classified map of Udham Singh Nagar is shown in Fig. 3.

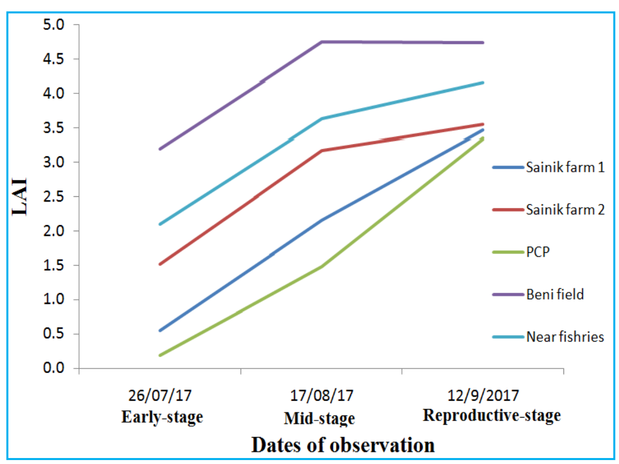

Fig. 4. Variations in observed LAI

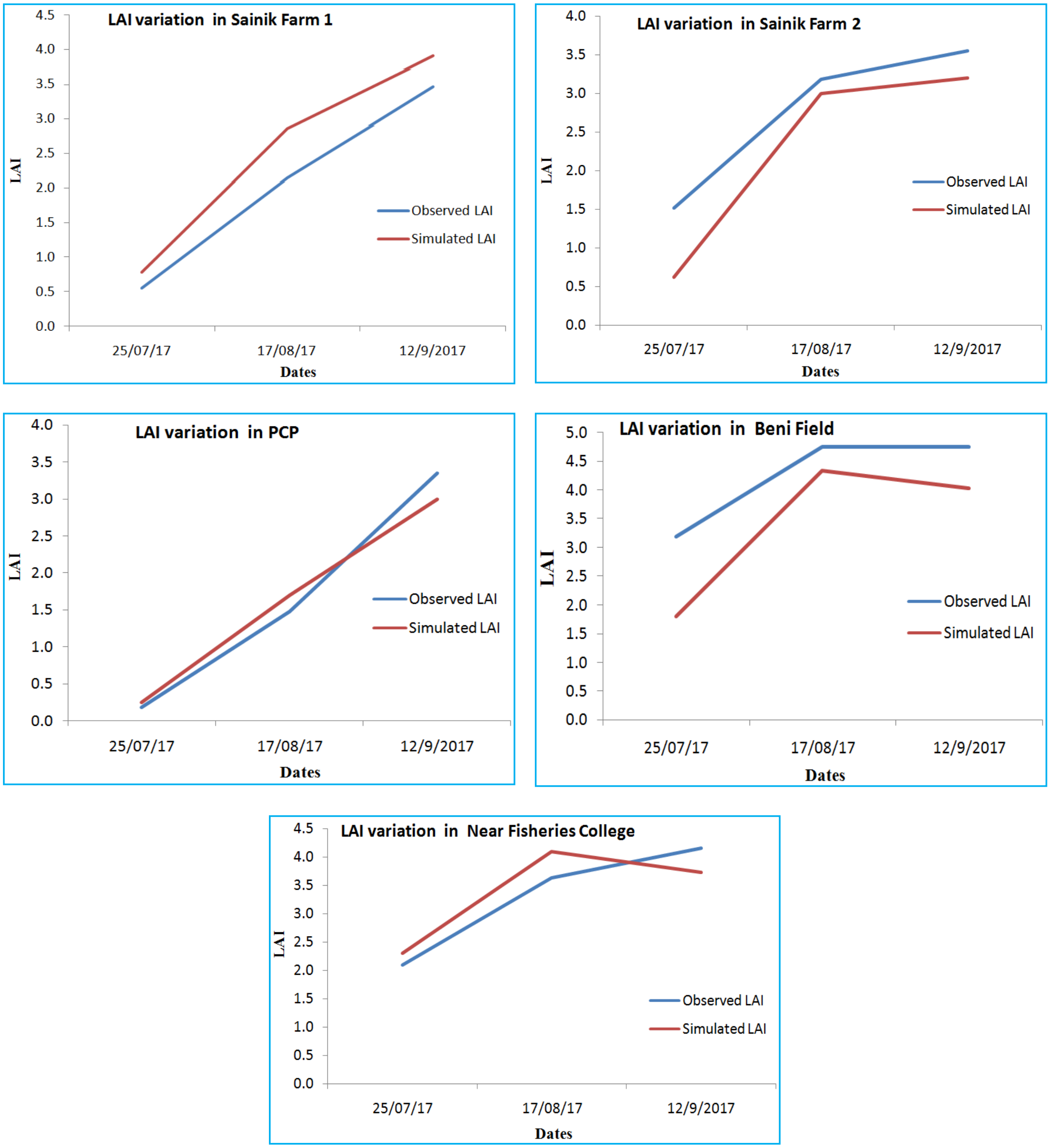

Fig. 5. Observed and simulated LAI for different Experimental Sites

The second phase was adjustment (calibration) of genotype coefficients of the rice cultivars by comparing simulated LAI with observed LAI of different fields. During the process of fine tuning or adjustment of the rice cultivars, the actual management file used as an input in the model, so that the genotype coefficients could precisely be adjusted. As, indicated in Table 3, field level production was calculated using the fine-tuned genotype coefficients.

The variations in observed LAI measured across five distinct fields using ceptometer at three crucial stages of rice (early, mid, and reproductive). The LAI of the rice plant increases with the increase in its growth. The LAI

TABLE 4

CERES-Rice simulated LAI and observed LAI

Place	Date	Observed LAI	Simulated LAI	RMSE (%)
Sainik farm 1	25/7/2017	0.55	0.78	24.30
	17/8/2017	2.16	2.86	
	12/9/2017	3.47	3.91	
Sainik farm 2	25/7/2017	1.51	0.62	20.50
	17/8/2017	3.18	3.00	
	12/9/2017	3.55	3.20	
PCP	25/7/2017	0.18	0.25	14.40
	17/8/2017	1.48	1.70	
	12/9/2017	3.35	3.00	
Beni Field	25/7/2017	3.19	1.80	22.10
	17/8/2017	4.75	4.33	
	12/9/2017	4.75	4.020	
Near Fisheries College	25/7/2017	2.09	2.30	11.70
	17/8/2017	3.63	4.09	
	12/9/2017	4.16	3.72	

increases rapidly from the early to mid-stage but then slows as the crop progresses to the reproductive stage for the five distinct fields are shown in Fig. 4. This is because the crop's initial foliar sections receive more food material partitioning, whereas reproductive organs are preferred over other parts of the plant in the later stage (Irving, 2015).

The 12 day repeat cycle of Sentinel-1A data satisfies the temporal resolution which is a need for this study and is very helpful in obtaining the biophysical parameters. The variance in crop LAI from field to field can be attributed to varied sowing dates, management practices, and cultivars. Because the crop in PCP and Sainik farm-1 was planted late, the LAI values in these two fields were low throughout the growth cycle when compared to other fields, as shown in Fig. 5 which depicts the temporal variation in LAI obtained from ground data and simulated observations for five different fields.

The integration of the crop simulation model CERES-Rice with SAR data was a key goal of the current study. To achieve this goal, the simulated LAI was compared with the observed LAI for fine tuning of the model. The fine-tuning of a genotype coefficient is a critical stage in the integration of remote sensing and crop simulation models. On numerous occasions, the effectiveness of remote sensing (both optical and passive) in obtaining LAI has been established (Manninen *et al*., 2005, Zheng and Moskal 2009, Jin *et al*., 2015). It has been envisaged in the study that if the LAI of crop simulation model matches well with observed LAI, the model can be used to predict district level rice yield. The temporal trend of the LAI was matched using varied sowing dates and further reduced using varied fertilizer doses. The water management in the model has been kept automatic as the district of Udham Singh Nagar receives plenty of rainwater with good irrigation facilities. The area has gross irrigated area of 248470 ha which covers more than 90% region (Directorate of Economics & Statistics, Ministry of Agriculture, Govt. of India). The fine tuned genotype coefficients of five different rice cultivars have been listed in Table 3.

The LAI simulated by the CERES-Rice model matched with observed LAI for 3 dates over five experimental plots are shown in Table 4. The comparison of observed and simulated LAI reveals that during the early stage of the crop, observed LAI values were relatively low compared to simulated LAI, however by the late stage of the crop, observed LAI values were reported more than simulated LAI. In comparison to simulated LAI, the observed LAI values of the Beni field were greater throughout the crop season. The RMSE between observed and simulated LAI varied between 11.7 and 24.3 percent. The RMSE value of the Beni field was much greater because the variety HKR-47 produced extraordinarily high LAI values that could not be picked by any combination of genotype coefficients.

As stated by Shen *et al.* (2009) during the re-initialization of the ORYZA 2000 model using the assimilation approach, the RMSE between simulated and observed LAI was less than 20.00% and may be deemed reasonably excellent. The ORYZA 2000 outputs were compared to in-field data collected over 10 fields in Jiangsu Province, China. With an RMSE of 12.20 percent, it was also discovered that the estimated rice yield was often higher than the measured rice production.

The observed and simulated coupled yields were found to be quite close. The measured rice yield in Sainik Farm 1 was 2582 kg/ha, while the simulated coupled yield was 2094 kg/ha, a discrepancy of 488 kg/ha. The measured rice yield for Sainik Farm 2 was 6129 kg/ha, while the simulated coupled yield was 6097 kg/ha, a 32 kg/ha discrepancy. The observed and simulated coupled yield for the PCP field were 1522 and 1458 kg/ha, respectively, with a 64 kg/ha difference. The measured yield of the Beni field was 3270 kg/ha, while the simulated coupled yield was 3244 kg/ha, representing a 26 kg/ha discrepancy. The observed yield of the field near the fisheries college was 2934 kg/ha, while the simulated

TABLE 5

Comparison of observed and coupled yield

Place	Observed Yield Kg/ha	Coupled Yield kg/ha	RMSE (%)
Sainik farm 1	2582	2094	
Sainik farm 2	6129	6097	
PCP	1522	1458	7.61
Beni Field	3270	3244	
Near Fisheries College	2934	3198	

TABLE 6

SAR retrieved LAI and Coupled LAI

Dates	SAR retrieved LAI	Coupled LAI	RMSE (%)
25/7/2017	1.97	1.44	
17/8/2017	2.47	3.26	22.1
12/9/2017	3.05	3.14	

TABLE 7

Coupled model and observed yield with yield difference

District name	Observed yield (kg/ha) (based on past five years average)	Coupled model Yield (kg/ha)	Difference in yield (kg/ha)
Udham Singh Nagar	3160	3190	30

coupled yield was 3198 kg/ha, resulting in a yield differential of 102 kg/ha. For varied fields, the RMSE between observed and coupled yield was determined to be 7.61 percent as shown in Table 5. Pazhanivelan *et al*. (2022) used an approach of integrating Sentinel-1A SAR data with the CERES-RICE model to estimate rice yield in Tamil Nadu's Cauvery delta districts, where they found an RMSE of less than 10.00%, indicating good agreement.

It was observed that the simulated coupled yield was higher at various experimental sites. This overestimation may be contributed to non-consideration of pests and disease attack on the rice crop which led to reduced yield. In a few situations, the simulated coupled yield was lower than the real yield because the partitioning coefficients that vary from one phenological stage to the next could not be fine-tuned well.

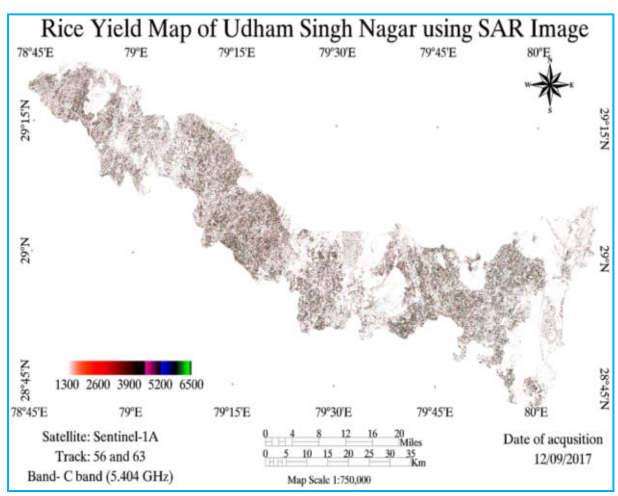

Fig. 4. Rice Yield Map of Udham Singh Nagar

This calibrated model was utilised to generate district-level LAI and the results were validated by comparing model-simulated LAI to SAR-retrieved LAI. The calibrated and validated model could now be combined with LAI obtained from the Sentinel-1A image to determine the yield for the Udham Singh Nagar district. In Table 6, simulation model's coupled LAI was matched with the mean values of LAI extracted from Sentinel-1A's multi-date images for the Udham Singh Nagar district.

The above table shows that the SAR retrieved LAIs were quite close to the coupled model with an RMSE of 22.1%. The yield generated by the coupled model is shown in Table 7**,** which is the representative yield of Udham Singh Nagar**.**

For the year 2017, the yield derived from the coupled model for Udham Singh Nagar was 3190 kg/ha. The average observed yield over the last five years, however, was 3160 kg/ha. The observed-coupled yield difference was 30 kg/ha, which is quite small. The CERES-Rice model is a lively, eco-physiological rice crop model that stimulates rice growth and development under situations of potential production, water stress, and nitrogen stress (Hussain *et al*., 2018). The daily calculation scheme is used in this model for the dry matter production rates and plant organ rates, as well as the rate of phenological development from emergence to harvest. The dry matter production of rice is simulated throughout the growth season by integrating these rates across time, and the final yield is computed (Tang *et al*., 2009). The semi-empirical rice backscatter model was calibrated and combined with CERES RICE to simulate VV/VH-polarized rice backscattering coefficients in order to create a district-wide rice yield map, as shown in Fig. 4.

4. Conclusion

When little in-situ information or inadequate optical data are available due to high clouds during a rice season, the system outlined in this article provides a feasible technique for using Sentinel-1A SAR data for regional rice yield prediction. The outcomes of the study showed that field level rice yield estimated through coupled approach ranged from 1458 kg/ha to 6097 kg/ha, while observed yield ranged from 1522 kg/ha to 6129 kg/ha. The RMSE computed between the yield generated by coupled model and the observed yield was 7.61%. The coupled model was also used to predict the district level rice yield. The yield generated by coupled model was 3190 kg/ha that was quite close to the average observed five year yield which was around 3160 kg/ha. This shows that coupled approach could be a reliable option for rice yield prediction. Though the above approach needs to be validated in different rice planting locations with varied SAR configurations, the current study is simply the first step in the direction of retrieving more and more crop biophysical characteristics using SAR data and replacing the model produced assimilates. As a result, further work should be devoted to improving the models and evaluating the system over longer series of data and across other sites. Therefore, we conclude that the integration of SAR data with CERES RICE model can be suggested to estimate the rice yield spatially.

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