

Cloud-Independent Mapping of Monsoon Rice Using Synthetic Aperture Radar

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INTRODUCTION

Rice (*Oryza sativa L.*) is an important staple crop in South and South East Asian countries especially India where Kharif rice is grown to a significant extent. Rice planting in the Kharif season being linked with the southwest monsoon it affects nursery establishment, transplantation, field flood and early vegetative growth. Rainfall variation has a high impact on the establishment of crops, water availability, and water productivity, and the use of puddled and shallow-flooded rice fields is a major feature of traditional lowland rice systems.

The traditional monitoring methods of rice include field survey, agricultural statistics and crop-cutting experiment. They are good for local-scale applications, but are time consuming, labour intensive and often late. The small-scale nature of smallholder fields and inconsistent smallholder transplanting date as well as the variability and heterogeneity of crop growth compounds monitoring. Optical sensor satellites like Sentinel-2 and Landsat's provide valuable data for crop assessment but have significant data gaps when the area is cloudy, which occurs often during monsoon season during key crop transplant and veg phases.

When sunlight is limited or absent, and/or if a user is willing to spend obtaining data, synthetic aperture radar (SAR) can be a powerful alternative, since it is not necessarily dependent on sunlight and is able to gather data through the cloud cover. Standing water and soil moisture and rice canopy structure are highly responsive to radar backscatter. As a result, multi-temporal SAR is highly appropriate for reliable monitoring of monsoon rice, with backscatter varying with the stage of the crop.

SAR Response of Paddy Rice: Physical Principles and Phenological Signatures

→ Microwave interaction with flooded rice fields

Microwave interactions with the surface water, soil and vegetation are the keys to the SAR response of paddy fields. Open water areas typically exhibit low backscatter due to the specular reflection away from the sensor that occurs from the surface of open water areas. Watering on the soil can vary with the depth of water and the surface. Young seedlings make little contribution in scattering and the water surface is always dominant after transplanting. As the rice grows, stems and leaves provide a greater interaction with the microwaves. The emerging and reaching stalks of stems above the water cause double bounce scattering and the spreading canopy generates volume scattering. At maturity, heavy vegetation, decreased exposure of surface water, and changing plant water content alter the radar response.

→ Rice phenology and temporal backscatter

Rice has specific temporal SAR signature from tillage and inundation to transplantation and tillering stage, stem elongation, reproductive stage, grain filling, maturity and harvest stage. Backscatter is typically high just after flooding and transplanting, but rises with vegetative growth, with increased biomass, stem density and canopy complexity. The scattering in the reproductive and grain filling stages continues to be affected by the characteristics of the canopy and by the amount of water in the vegetation, but during the maturity and harvest stages the scattering may decrease or change rapidly. So multi-temporal SAR is more useful than a single image, as this resulted in seeing the whole phenological path, and also raised the possibility of differentiating rice from other land cover classes with similar backscatter at a particular time.

→ Polarization and paddy discrimination

Polarization is the direction of the transmitted and received microwave polarization. HH and VV are co-polarized configuration, HV and VH are cross-polarized configurations. Surface scattering and double-bounce scattering are important sources of effect on co-polarized signals and so are the structures and volume scattering in vegetation on cross-polarized signals. A change from co- to cross-polarized observations effectively assists in differentiating rice from open water, moist fallow land and other vegetation by using multi dates.

→ Important SAR parameters

Normally, rice backscatter is written as the normalized backscattering coefficient. Its magnitude is incident angle, wavelength, polarization, surface roughness, dielectric properties, moisture content of the soil and water content of the vegetation. Volume scattering increases with canopy development, while double bounce scattering is significant when there are vertical stems and flooded surfaces. Further information regarding time (temporal) coherence can also be used to inform the stability of structures and enable the quick detection of temporal changes in the field during flooding, growth and harvest of crops.

Evolution of Satellite SAR for Rice Monitoring: RISAT-1, Sentinel-1 and NISAR

→ ISRO RISAT-1: Operational Experience in Indian Paddy Monitoring

RISAT-1 was a valuable platform to develop rice monitoring using SAR in operation in India. It was launched by ISRO in 2012 and had on it indigenous C-band SAR which was developed for operation around 5.35 GHz allowing day/night and nearly any weather conditions observations of agriculture. This capability was especially useful for kharif rice where cloudy monsoon weather often hinders

optical satellite data acquisition. Changes in rice fields have been characterized using multi-temporal HH and HV polarization data for the stage of transplantation, tillering and peak vegetative growth. Transplanted flooded fields, in general, exhibited lower radar backscatter recently transplanted, but the greater stem density, canopy growth and biomass increasingly altered the radar backscatter. Cross-polarized HV observations proved specific and valuable for vegetation

development and for minimizing vegetation and water/moist fallow surface confusion. The RISAT-1 studies has shown applications in rice acreage estimation, detection of transplantation-date detection and biomass retrieval. These investigations confirmed the potential use of multi-date C-band SAR data for agriculture assessment and also showed how the phenology of crops could be correlated with radar measurements.

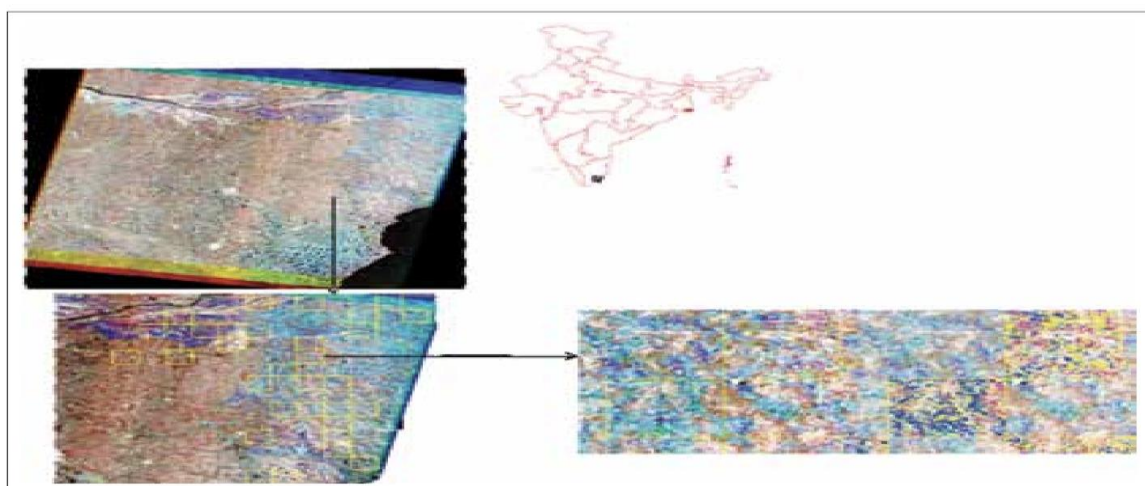


Fig. 1: RISAT -1 MRS 3-date-HH composite (25/10, 19/11 and 14/12/2012) of Tamil Nadu -Thanjavur Pudukottai and Shivagangai Districts Zoomed view for Thanjavur dist. showing first date (blue) second (yellow) and third (magenta) date transplanted rice

→ Sentinel-1: Large-Scale Operational Rice Mapping

As soon as systematic, frequent, C-band data became available via the Copernicus Sentinel-1 mission and were free to use, Rice monitoring using SAR was revolutionized. Agricultural information is often captured by Sentinel-1 in VV and VH polarizations that result in complementary information on surface-water conditions and the structure of the plants. Paddies even after transplantation, and in particular those which are flooded, exhibit a radar response which is peculiar. This is followed by an increasing radar backscatter level with the advance of tillering, canopy, and biomass. Thus, multi-temporal Sentinel-1 data can be used in rice-area mapping, estimation of

transplanting dates, phenological monitoring and in cropping-intensity assessment. Since waterlogged surfaces are very sensitive to radar, this feedback also allows monitoring of flooding, and out-of-envelope radar backscatter trends can be used to monitor crop development delay or drought. One of the key benefits is easy integration with cloud computing solutions such as Google Earth Engine, which provide the access to large archives of Sentinel-1 data to be used in thresholding, timeseries and machine-learning classification. This cloud-independence coupled with multiple acquisitions and open data has allowed for extensive rice monitoring at a consistent scale, over large monsoon dominated agricultural landscapes.

→ NASA–ISRO NISAR: A New Generation of Rice Monitoring

In January 2026, the NASA–ISRO Synthetic Aperture Radar (NISAR) mission had begun science operations, offering 12-day exact repeat cycle with broad, high-resolution observations, which is a big leap forward for agricultural radar remote sensing. The longer L band wavelength is able to probe deeper into the crop structure and the underlying soil while S band is sensitive to near surface conditions and smaller canopy structures. For rice systems, this dual-frequency capability can enable rice acreage mapping, estimation of rice transplanting dates, rice phenological

monitoring and crop-height, biomass assessments, soil-moisture retrieval and characterization of paddy-water. Water stress, abnormal flooding, and lodging and crop damage could then be detected through deviations of the radar trajectories from the expected trends for the same season repeatedly observed. NASA indeed points out the potential for estimating rice planting dates and monitoring rice crop height, flowering and wetness. NISAR offers a new approach to monitor rice quantitatively from establishment to harvest with multi-parameters in an openly accessible data.

Comparative characteristics of major SAR missions for rice monitoring

Parameter	RISAT-1	Sentinel-1	NISAR
Agency	ISRO	ESA/Copernicus	NASA–ISRO
Primary SAR band	C-band	C-band	L-band + S-band
Frequency/wavelength	5.35 GHz / ~5.6 cm	~5.405 GHz / ~5.6 cm	L: ~24 cm; S: ~9.4 cm
Important polarizations for rice	HH, HV	VV, VH	Multiple polarimetric modes
Exact repeat	25 days	12 days per satellite	12 days
Major strength	Indian operational paddy applications	Frequent, open, large-scale monitoring	Dual-frequency crop characterization
Rice-area mapping	✓	✓✓	✓✓
Transplanting-date detection	✓	✓✓	✓✓
Phenological monitoring	✓	✓✓	✓✓✓
Biomass monitoring	✓	✓✓	✓✓✓
Paddy-water monitoring	✓	✓✓	✓✓✓
Soil-moisture potential	Moderate	High	Very high
Data access	Mission/archive dependent	Free and open	Free and open
Key contribution	Established Indian SAR rice monitoring	Enabled scalable operational mapping	Integrates structure, moisture and crop development

✓ = useful, ✓✓ = strong capability, ✓✓✓ = particularly promising capability

Advanced Approaches for Cloud-Independent Monsoon Rice Mapping

→ Multi-temporal SAR time-series analysis

The monitoring of the seasonal changes of rice field based on multi-temporal SAR analysis. Temporal profiles of VV, VH, HH or HV backscatter images record the temporal process from land preparation to flooding, to transplanting to tillering to the reproductive developmental stages and maturity. Phenology based thresholds can assist in helping discern significant changes, such as the decrease in backscatter as fields flood followed by similar increases as canopy starts to grow. These seasonal trajectories could be used for transplanting-date estimation and identifying and detecting crop-stages. The time-series analysis is more reliable than a single date imagery since it can differentiate rice from wetlands (non-crop) and other crops which display similar radar response at any given crop growth stage.

→ SAR–optical data fusion

The SAR–optical data fusion method integrates SAR data, which can capture the surface moisture and vegetation structure, with optical sensor data, which can convey spectral information. Normally the Sentinel-1 and Sentinel-2 are working in tandem since the optical data can be used to generate vegetation indices and crop-condition observations during clear weather conditions, while the radar data is available during cloudy conditions. The same research can be combined with Landsat or Sentinel-2 as well and RISAT and with NISAR as well. Fusion may be done at each pixel, feature or decision level. These approaches enhance the mapping of rice areas, the identification of transplanting dates and the evaluation of rice phenology and stress and minimize the lack of information due to continuous cloudiness in the monsoon season.

→ Machine learning and deep learning

Modelling of complex spatial and temporal relationships between remote-sensing variables, using machine-learning and deep-learning algorithms, enhances rice classification. XGBoost, Support Vector Machine and Random Forest are able to classify the rice with the backscatter, polarization ratios, vegetation indices and texture features. ArtificialNNs-To model nonlinear relationships, and CNNs-To extract spatial patterns from imagery. They are particularly well suited to the sequential temporal data of the time-series since the LSTM networks are able to understand trajectories of a crop's development. Transformer-based methods are able to consider longer temporal dependencies. Temporal machine learning will be useful in separation of rice from permanent water, sugarcane, maize and others irrigated crops due to different flooding timelines, planting and growing season cycles.

→ Cloud computing

Cloud-computing platforms make it possible to run large scale rice monitoring, thus enabling an extensive archive of satellites to be processed quickly and does not require a huge local computing capability. Google Earth Engine (GEE) provides an automated platform for Sentinel-1, Sentinel-2, Landsat and all other datasets to extract time-series and classify data. NASA Earthdata hosts many different products from earth observation and the Alaska Satellite Facility facilitates distribution of SAR data, including NISAR products, and cloud-based access. Bhoonidhi are the agencies responsible for the dissemination of earth observation data, including the NISAR S-band data, and Bhuvan for the geospatial visualization and thematic applications in India. They allow scalable and reproducible and automated rice monitoring workflows in larger monsoon agricultural areas.

→ Mapping outputs

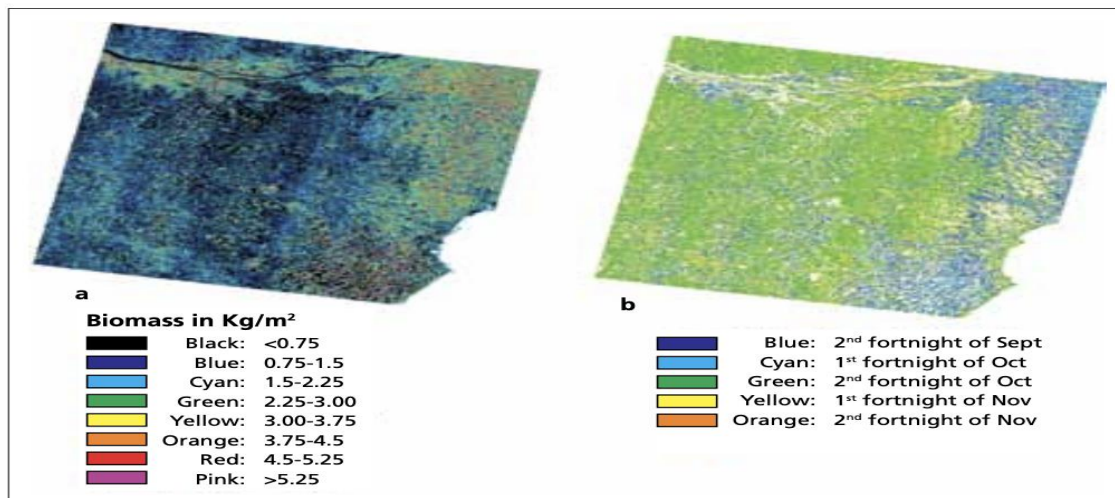


Fig. 2: (a) Biomass map (b) Transplantation date Map using three date RISAT data

In rice monitoring and rice management, there are a number of important outputs, which are derived by advanced SAR and multisensory approaches. Using rice/non-rice maps, spatial estimates of cultivated area are provided, and with the aid of transplantation-date maps, crop-initiation periods are also identified. Phenology maps are those that show significant phenological events, such as the vegetative phase, reproductive phase and phase of maturity. Biomass maps show crop development at the point level, and flooded-area maps help pinpoint waterlogged fields as well as potential damage from flooding. Yield related indicators involve consideration of biomass as well as phenology, moisture content and seasonality of the backscatter. The results are used to estimate acres, plan irrigation, forecast crops, and evaluate floods and droughts and make targeted agricultural decisions for food-security analysis.

Challenges, Future Opportunities and Research Roadmap for Monsoon Rice Monitoring

→ Current limitations

Speckle, mixed pixels, fragmented fields, incidence-angle and terrain effects all have

impact on the SAR based rice mapping. Classification is made even more complex by the variable transplanting dates, the different irrigation practices, the various rice varieties, the different direct seeding systems, and SRI systems and spectral similarity with wetlands. Also, model transferability is limited with a limited field validation.

→ Opportunities from NISAR

It's a seamless transition from RISAT-1 to Sentinel-1 to NISAR, which allows for more and more information about rice to be delivered at a more frequent rate. Observations by NISAR's L-band and S-band sensors will enhance the detection of crop structure and moisture, biomass and changes in agricultural seasons.

→ SAR + AI + crop models

Future systems to incorporate SAR, optical EO, meteorology, crop models, AI and field IoT. Incorporating the NISAR radar backscatter data with the Sentinel-2 vegetation indices, rain data and soil moisture and crop model simulations might lead to better rice-yield prediction.

→ Climate-resilient rice monitoring

Integrated monitoring can help in early assessment of drought, floods, delayed and anticipated monsoons, cyclone damage, salinity, and water scarcity and improve crop insurance, disaster response, and food security assessment.

→ Future research roadmap

India needs a national operational rice-monitoring framework involving multi-frequency SAR, optical imagery, weather information, crop models, AI and field observation for near-real-time agricultural monitoring for acreage, phenology, stress, yield and damage assessment.