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SYNTHETIC APERTURE RADAR IN AGRICULTURE: APPLICATIONS, ADVANCES, AND FUTURE PROSPECTS

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Agricultural systems increasingly demand continuous, high-resolution monitoring to support food security, climate adaptation and precision farming. Traditional field-based observations, although accurate, are spatially limited and resource-intensive, while optical satellite remote sensing is frequently constrained by cloud cover, haze and revisit gaps-challenges that are particularly acute in monsoon-dominated and tropical agricultural regions. Synthetic Aperture Radar (SAR) addresses these limitations through active microwave sensing, enabling data acquisition independent of sunlight and largely unaffected by clouds, smoke or atmospheric conditions. This makes SAR uniquely suited for year-round agricultural surveillance, especially during critical growth phases that coincide with persistent cloud cover.

SAR backscatter is sensitive to biophysical properties such as soil moisture, surface roughness, crop structure, biomass and flooding status. These sensitivities allow systematic monitoring of sowing patterns, growth stages, irrigation cycles, harvest timing and post-harvest management across diverse landholdings-from smallholder farms to industrial cropping systems. Furthermore, modern SAR missions, such as Sentinel-1 and upcoming dual-band systems like NISAR, provide frequent, high-resolution observations that can be integrated with optical, thermal and ground-based datasets to enable advanced analytics including machine learning, data fusion and model-driven yield forecasting.

In this context, SAR is transitioning from a niche scientific tool to a foundational technology for climate-smart, data-driven agriculture and policy decision-making.

Fundamentals of Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is an active microwave remote sensing system that transmits electromagnetic pulses toward the Earth's surface and measures the energy scattered back to the sensor. Unlike passive optical instruments that rely on reflected sunlight, SAR

operates independently of illumination and can penetrate clouds, haze and smoke, making it well-suited for agricultural landscapes where critical growth stages coincide with monsoon or overcast conditions. SAR sensors are typically mounted on satellites or aircraft and operate in a side-looking geometry. High spatial resolution is achieved computationally by synthesizing a long virtual antenna from successive radar echoes collected along the platform's flight path- a principle known as *synthetic aperture processing*.

Several system parameters determine how SAR interacts with agricultural surfaces:

- Frequency/Wavelength Bands: X-band (~3 cm) responds to fine canopy features; C-band (~5–6 cm), used by missions such as Sentinel-1 and RISAT, captures both soil and crop canopy dynamics; L-band (~23 cm), deployed in missions like ALOS-2 and NISAR, penetrates deeper into vegetation and is advantageous for biomass and agroforestry monitoring.
- Polarization (VV, VH, HH, HV): Co-polarized channels are typically sensitive to soil moisture and surface scattering, while cross-polarized channels capture volume scattering from stems and foliage.
- Incidence Angle and Spatial Resolution: These influence sensitivity to roughness, moisture and canopy structure, often requiring normalization for large-scale analyses.

Together, these parameters determine the quantitative value of SAR for retrieving agricultural biophysical variables and building time-series analytics across seasons.

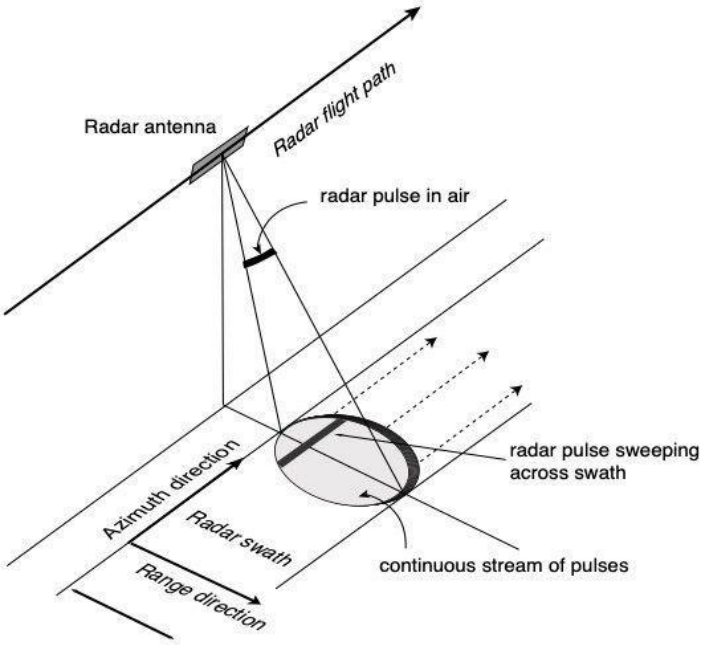

Fig. 1: working mechanism of SAR

SAR Interaction with Agricultural Targets

Agricultural landscapes present complex and rapidly changing microwave scattering environments where soil moisture, canopy architecture, residue cover and management practices jointly influence radar backscatter. Unlike natural forests, crop fields undergo fast phenological transitions-from bare soil to full canopy and back to harvested surfaces-resulting in distinct temporal signatures that can be exploited for crop monitoring, sowing date detection and growth-stage mapping.

Three dominant scattering mechanisms govern the SAR response over croplands:

- Surface Scattering: Predominant in early-season and post-harvest conditions when vegetation is sparse. Backscatter is largely driven by soil dielectric properties, which increase with moisture content, and by surface roughness influenced by tillage, ridging and crusting. Co-polarized channels (VV/HH) are particularly sensitive during this stage.
- Volume Scattering: As crops develop, stems, leaves and panicles introduce multiple scattering pathways within the canopy. Cross-polarized channels (VH/HV) capture this complexity and often correlate with biomass, leaf area index (LAI) and canopy height, although saturation may occur at high biomass levels.
- Double-Bounce Scattering: Occurs when upright vegetation overlays water or saturated soil, producing strong dihedral reflections. This mechanism is characteristic of flooded rice paddies, irrigated lowlands, or residue standing over wet soil and is highly useful for transplanting detection, irrigation tracking and flood mapping.

These mechanisms evolve seasonally, producing distinctive multi-temporal backscatter trajectories. For example, rice fields show sharp transitions during flooding and transplanting, whereas maize exhibits gradual volume-scattering peaks during rapid vegetative growth. Understanding these interactions is fundamental to deriving biophysical parameters and interpreting SAR-based agricultural models.

SAR Data Sources and Processing Pipelines for Agriculture

The operational use of SAR in agriculture has advanced rapidly due to the availability of open-access satellite missions, improved spatial and temporal resolutions, and scalable cloud-based processing environments. Sentinel-1 (C-band) has become the most widely used dataset globally because of its 6–12-day revisit cycle, dual-polarization capability, and free

access, making it suitable for crop mapping, flood monitoring, and soil moisture analytics. Other major missions include ALOS-2 (L-band) for biomass and agroforestry applications, TerraSAR-X (X-band) for fine structural monitoring, RADARSAT Constellation for agricultural compliance and disaster assessment, and India's RISAT-1A/EOS-04, which supports monitoring in monsoon-prone cropping regions. The upcoming NISAR mission, with systematic global L- and S-band coverage, is expected to significantly enhance retrievals of crop structure, residue cover, and perennial systems.

To derive meaningful agricultural insights, SAR data undergo a structured preprocessing chain: radiometric calibration to obtain backscatter coefficients (σ^0), speckle filtering to improve interpretability, terrain and geometric correction for accurate geolocation, and incidence-angle normalization to ensure consistency across tracks. Time-series stacking further enables phenology tracking, irrigation event identification, and change-detection analytics. These workflows are increasingly executed on platforms such as Google Earth Engine, SNAP, Open Data Cube, DIAS, Bhuvan, and custom machine-learning pipelines, reducing computational barriers and enabling near real-time agricultural monitoring.

Core Agricultural Applications of SAR

The distinctive sensitivity of radar backscatter to soil moisture, vegetation structure and hydrological conditions enables SAR to support a wide spectrum of agricultural applications, ranging from crop inventory and phenological monitoring to yield estimation and disaster loss assessment. As multi-temporal SAR datasets have become denser and more accessible, their role has shifted from exploratory research to operational crop intelligence systems used by governments, insurers and climate-risk platforms. The key application domains are summarized below.

Crop Type Mapping and Acreage Estimation

SAR time-series capture crop-specific backscatter trajectories arising from differences in planting dates, water regimes, canopy structure and harvest patterns. Rice paddies, for instance, show distinct double-bounce signatures during flooding and transplanting, whereas dryland crops such as maize and wheat exhibit gradual increases in cross-polarized backscatter during vegetative growth. These temporal fingerprints allow supervised machine-learning and phenology-based classification to discriminate crops even when optical imagery is unavailable due to cloud cover. Combined SAR–optical fusion further enhances separability in mixed or

fragmented landscapes, making SAR essential for national crop inventory schemes, food security assessments and policy-linked acreage reporting.

Crop Growth Monitoring and Phenology Detection

Because SAR captures structural and moisture-driven changes throughout the crop lifecycle, time-series signals can be used to identify phenological transitions such as sowing, transplanting, tillering, flooding, flowering and harvest. Transition points can be detected automatically using break-point algorithms, time-series smoothing models or state-space approaches. These phenological profiles support in-season monitoring, early-warning advisories, crop calendar validation and retrospective attribution of production variability to management or climate anomalies. Such capabilities are especially valuable in monsoon regions where optical observations are obstructed during critical growth phases.

Soil Moisture, Waterlogging and Irrigation Dynamics

Soil dielectric properties increase sharply with volumetric water content, making SAR-particularly co-polarized C- and L-band observations-highly sensitive to surface moisture under low to moderate vegetation cover. Retrieval approaches range from empirical regressions to physically based models such as the Water Cloud Model, with recent advancements integrating machine learning and multi-sensor fusion to reduce uncertainties in roughness, slope and vegetation attenuation. Time-series analysis also supports detection of irrigation cycles, canal water delivery, and post-rain infiltration patterns, enabling assessment of water-use efficiency, drought impacts and hydrological interventions. In flood-prone agroecosystems, SAR's ability to map inundation beneath vegetation can inform disaster assessment and relief planning.

Above-Ground Biomass and Yield Estimation

Cross-polarized backscatter is often correlated with biomass accumulation, canopy height and LAI during vegetative stages. At longer wavelengths (e.g., L-band), penetration through upper canopy layers enhances sensitivity to structural attributes of crops and agroforestry systems. Yield estimation frameworks increasingly combine SAR-derived biophysical metrics with process-based crop growth models, statistical regressions or hybrid deep learning architectures. These integrations support pre-harvest yield forecasting, carbon budgeting, residue assessment and monitoring of resource-use efficiencies, particularly where field data are limited or optical indices saturate at high biomass.

Damage Assessment and Extreme Events

SAR is widely used to detect and quantify agricultural damage caused by floods, cyclones, hailstorms, lodging, drought and pest outbreaks. Flood detection relies on strong backscatter drops over open water and characteristic dihedral returns when vegetation stands in inundated fields. Lodging events alter canopy geometry, causing distinct changes in coherence and backscatter intensity, enabling insurance-oriented crop loss estimation. Unlike optical sensors, SAR allows rapid assessment during cloudy emergency conditions, making it critical for disaster-response programmes, post-cyclone crop loss verification and climate-risk modelling.

Monitoring Tillage, Residue, and Conservation Agriculture

Radar is sensitive to surface roughness and the structural arrangement of residue cover, allowing detection of tillage intensity, mulch persistence and residue-burning events. C-band signals respond strongly to changes in surface scattering, whereas L-band observations help separate residue structure from soil moisture effects. These metrics support carbon-farming programmes, regenerative agriculture schemes, soil conservation compliance and greenhouse gas inventories. Combined with metadata on crop rotations and fertilizer management, SAR can contribute to monitoring, reporting and verification (MRV) systems for sustainability and carbon-credit frameworks.

Emerging Trends: From PolSAR and InSAR to Deep Learning and Data Fusion

Recent advancements in sensing technology and computational analytics are transforming SAR from a predominantly backscatter-based monitoring tool into a multidimensional framework for structural, biophysical and process-level agricultural inference. Polarimetric SAR (PolSAR) systems enable full polarization acquisition, allowing scattering decomposition into surface, dihedral and volume components. Metrics such as entropy, anisotropy, alpha angle and the Radar Vegetation Index (RVI) provide enhanced sensitivity to crop architecture, residue cover, canopy water content and biomass dynamics. Compact-pol systems now offer a cost-effective alternative to quad-pol acquisitions, expanding scalability for operational agricultural monitoring.

In parallel, Interferometric SAR (InSAR) and Polarimetric InSAR (PolInSAR) techniques exploit phase differences across time or polarization channels to retrieve canopy height, vertical structure and subtle terrain deformation linked to groundwater extraction, land

subsidence and irrigation cycles. These capabilities are particularly relevant for tree-based cropping systems, perennial agroforestry landscapes and carbon accounting frameworks. Dual-frequency, high-revisit missions such as NISAR are expected to further advance operational use of these techniques by enabling global, systematic L- and S-band observations.

Concurrently, the integration of SAR with deep learning, biophysical models and multisensor fusion platforms is enabling end-to-end agricultural intelligence pipelines. Combining SAR with optical, thermal, LiDAR, UAV and ground sensors enhances yield prediction, soil moisture retrieval and anomaly detection in cloud-prone regions. Access to scalable platforms-such as Google Earth Engine, Open Data Cube and national digital agri-stacks-is accelerating deployment of SAR-based products in crop insurance, sustainability certification and climate-resilience planning.

Challenges, Limitations, and Research Gaps

Despite its growing prominence in agricultural monitoring, several technical and operational limitations constrain the full-scale deployment of SAR-based analytics. A fundamental challenge lies in the non-unique relationship between backscatter and biophysical variables, as soil moisture, surface roughness and vegetation structure often produce overlapping signals, complicating inversion models. Saturation effects at high biomass, limited availability of quad-polarimetric data and uncertainties arising from incidence angle variation further constrain quantitative retrievals. Soil moisture estimation remains particularly challenging under dense canopies, necessitating multi-frequency sensing or physics-guided machine learning.

Operational constraints also persist. Speckle, layover and shadowing reduce interpretability in heterogeneous terrain, while the computational cost of processing large time-series datasets remains significant for institutions without high-performance infrastructure. Although cloud platforms reduce barriers, they require skilled personnel trained in microwave physics and data analytics-expertise that is still limited in agricultural agencies and extension systems, especially in smallholder-dominated regions.

A major research gap lies in the lack of harmonized ground-truth datasets for calibration and validation across diverse agro-ecological zones. Integrating SAR with crop models, IoT sensors and soil–plant simulations remains an emerging frontier, as does translating SAR-derived indicators into actionable, farmer-friendly advisories. Addressing these gaps is

essential for transitioning SAR from scientific potential to operational agricultural decision-making.

Conclusion

As agriculture confronts the twin pressures of climate instability and rising production demand, SAR is becoming integral to digital agrometeorology, landscape monitoring and climate-smart decision support. Its ability to capture soil moisture dynamics, inundation, phenology and canopy structure under persistent cloud cover makes it uniquely suited for monsoon-dominated and tropical farming systems, where traditional optical monitoring frequently fails. The advent of high-revisit missions such as Sentinel-1 and dual-frequency systems like NISAR will expand the spatial and temporal resolution of agricultural observations, particularly in perennial horticulture and agroforestry domains where canopy penetration and structural retrieval are essential.

The future of SAR lies not only in improved sensors but in full eco-informatic integration, where radar signals merge with optical, thermal, UAV, IoT and ground-truth datasets to create operational crop intelligence pipelines. With machine learning, biophysical modelling, and automated change detection, SAR can support real-time crop insurance validation, carbon accounting, regenerative agriculture monitoring and resource-use efficiency assessments. Unlocking its full potential, however, will require investments in capacity building, open infrastructures, and harmonized field datasets. If these barriers are addressed, SAR will serve as a cornerstone technology for resilient, transparent and data-driven agricultural systems.

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