International Journal of Bioresource Science
Citation: IJBS: **12**(02): 259-271, December 2025
DOI: 10.30954/2347-9655.02.2025.13

ASSOCIATION FOR AGRICULTURE ENVIRONMENT AND BIOTECHNOLOGY

REVIEW PAPER

Remote Sensing and Its Role in Shaping Forest Crescendos under Climate Change

Miriam W. Githumbi[1], Riziki Mwadalu[2], Joseph Onyango-Gweyi[1], Jacob Omollo[3], Sumit Sow[4], Shivani Ranjan[4], Sagar Maitra[5] and Harun I. Gitari[1*]

[1]Department of Agricultural Science and Technology, School of Agriculture and Environmental Studies, Kenyatta University, Nairobi, Kenya
[2]Central Highlands Eco-Region Research Programme, Kenya Forestry Research Institute, Nairobi, Kenya
[3]Kenya Sugar Research and Training Institute, Miwani Road, Kisumu, Kenya
[4]Department of Agronomy, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India
[5]Department of Agronomy and Agroforestry, Centurion University of Technology and Management, Paralakhemundi, Odisha, India

*Corresponding author: hgitari@gmail.com (**ORCID ID:** 0000-0002-1996-119X)

Received: 28-08-2025 **Revised:** 12-11-2025 **Accepted:** 27-11-2025

ABSTRACT

Forests serve as critical regulators of the global climate through carbon sequestration, biodiversity conservation, and ecosystem services. Nonetheless, climate change is fundamentally disrupting these functions by driving shifts in species distributions, reducing biomass productivity, altering carbon storage capacity, and intensifying disturbance regimes such as wildfires, pest outbreaks, droughts, and storms. Such transformations threaten forest resilience and challenge sustainable management, necessitating advanced monitoring tools capable of capturing complex, multi-scale ecological responses. Remote sensing technologies, including satellite-based optical sensors (Landsat, Sentinel, MODIS), radar systems, LiDAR, hyperspectral imaging, and unmanned aerial vehicles (UAVs), provide indispensable insights into forest canopy structure, phenological cycles, biomass dynamics, and physiological stress indicators like chlorophyll fluorescence and water deficits. Integration of these technologies with machine learning (ML), artificial intelligence (AI), and ecological models enables unprecedented detection of subtle climate-driven impacts and predictive capacity for ecosystem shifts. Key advances include Sentinel-1/2 fusion for cloud-free deforestation monitoring, GEDI-Landsat integration, enhancing biomass estimation accuracy by 30% and convolutional neural networks (CNNs) achieving >90% accuracy in early pest outbreak detection. Despite persistent challenges such as tropical cloud cover, scaling mismatches, computational demands, and ground-validation gaps, remote sensing has become fundamental for informing climate adaptation strategies, conservation planning, and policy frameworks like REDD+. This chapter synthesizes technological innovations, regional case studies, and emerging opportunities to advance predictive monitoring and strengthen forest resilience under accelerating climate change, bridging critical gaps between scientific research and actionable management solutions.

HIGHLIGHTS

- Climate change has intensified calamities such as wildfires, pest outbreaks, droughts, and storms in forest ecosystems, thus threatening forest resilience and challenging sustainable management.
- Remote sensing technologies provide indispensable insights into forest canopy structure, phenological cycles, biomass dynamics, and physiological stress indicators.
- Such technologies can be integrated into machine learning (ML), artificial intelligence (AI), and ecological models for the detection of subtle climate-driven impacts.

Keywords: Forest dynamics, Remote sensing, Hyperspectral imaging, Carbon storage, Forest productivity

How to cite this article: Githumbi, M.W., Mwadalu, R., Onyango-Gweyi, J., Omollo, J., Sow, S., Ranjan, S., Maitra, S. and Gitari, H.I. (2025). Remote Sensing and Its Role in Shaping Forest Crescendos under Climate Change. *Int. J. Bioresource Sci.*, **12**(02): 259-271.

Source of Support: IUCEA; **Conflict of Interest:** None

Forests cover 31% of the global land area and serve as vital carbon sinks, biodiversity reservoirs, and regulators of hydrological cycles, storing nearly 45% of terrestrial carbon in their biomass, soils, and dead organic matter (Vogt *et al*. 2019; Emmanuely *et al*. 2025; Luciana *et al*. 2025). Through photosynthesis, forests sequester atmospheric carbon dioxide while simultaneously influencing surface energy balance, evapotranspiration, and regional climate patterns (Maitra *et al*. 2020; Nyawade *et al*. 2021; Masina *et al*. 2023; Gitari *et al*. 2024). These multifaceted roles make forests indispensable for climate mitigation, biodiversity conservation, and human well-being. However, anthropogenic climate change, characterized by rising temperatures, altered precipitation regimes, and increased frequency of extreme events, is fundamentally disrupting forest dynamics worldwide (Santosh *et al*. 2024; Ray *et al*. 2024; Maitra *et al*. 2025a). These disruptions manifest as accelerated species range shifts, altered phenological timings, heightened disturbance regimes (wildfires, pests, storms), and declining carbon sequestration capacity (Emmanuely *et al*. 2024; Mukesh *et al*. 2024; Nungula *et al*. 2025; Maitra *et al*. 2026). For instance, tropical forests are transitioning from carbon sinks to sources due to drought-induced mortality, while boreal ecosystems experience biome-scale expansions and contractions driven by permafrost thaw and lengthening fire seasons (Hubau *et al*. 2020; Manasa *et al*. 2021; Seidl *et al*. 2017; Soratto *et al*. 2022; Maitra *et al*. 2024a).

Traditional field-based monitoring, though precise, lacks the scalability to capture these complex, large-scale changes, creating urgent demand for innovative remote sensing solutions (Wulder *et al*. 2020). Remote sensing technologies have revolutionized forest monitoring by providing synoptic, multi-temporal, and multi-dimensional data on vegetation structure, function, and health (Sow *et al*. 2024). Satellite-based optical sensors (Landsat, Sentinel-2) track deforestation and phenological shifts over five decades, while radar (Sentinel-1) and LiDAR (GEDI) penetrate cloud cover to quantify 3D canopy structure and biomass (Dubayah *et al*. 2010; Reiche *et al*. 2021). Hyperspectral sensors detect physiological stress indicators (chlorophyll decline) before visible symptoms appear, enabling early intervention. Concurrently, machine learning (ML) and artificial intelligence (AI) approaches, particularly convolutional neural networks (CNNs) and random forests, automate the extraction of complex patterns from petabyte-scale datasets, enhancing the detection of disturbances like pest outbreaks and drought stress with >90% accuracy (Wagner *et al*. 2023).

Despite these advances, critical gaps persist. Single-sensor approaches fail to capture the multifaceted nature of climate impacts, while data harmonization across platforms remains challenging (Asner *et al*. 2017). Computational demands limit accessibility in developing regions, and integrating remote sensing with ecological models requires further refinement (Schimel *et al*. 2015). This chapter addresses these gaps by synthesizing: climate-driven alterations in forest dynamics, remote sensing technologies and their integration, advanced analytical approaches (ML/AI, model coupling), and challenges and future directions. By evaluating the synergies between multi-sensor remote sensing, AI analytics, and ecological modeling, we highlight pathways toward scalable, predictive monitoring of forest resilience under accelerating climate change, bridging critical gaps between scientific research and actionable management solutions for conservation, policy frameworks like REDD+, and adaptive forest management.

FOREST DYNAMICS UNDER CLIMATE CHANGE

Climate change is fundamentally reshaping forest dynamics by altering species distributions, productivity, disturbance regimes, and ecosystem resilience worldwide (Raj *et al*. 2025). Rising temperatures and shifting precipitation patterns drive poleward and upslope migrations of tree species, leading to novel community assemblages, range contractions, and local extinctions where dispersal is limited by geographic barriers or fragmented landscapes (Boisvert-Marsh *et al*. 2019; Nungula *et al*. 2023). Tropical forests face heightened vulnerability, with drought-sensitive species declining and less carbon-dense taxa gaining dominance (Mwadalu *et al*. 2025). These biome shifts threaten ecosystem stability, potentially replacing boreal forests with temperate species and forcing montane communities to higher elevations. Carbon sequestration capacity is increasingly compromised. While elevated CO_2 initially boosted photosynthesis in some regions, these gains are now offset by drought stress, nutrient limitations, and temperature-induced mortality (Ainsworth and Long, 2021; Cheptoek *et al.* 2021). Long-term monitoring reveals declining carbon sink strength in tropical forests, particularly the Amazon and Africa, as mortality rates outpace growth (Hubau *et al.* 2020; Chappa *et al.* 2024). This trend risks converting forests from net carbon absorbers to emitters, amplifying climate feedback loops (Fig. 1).

Disturbance regimes are intensifying in frequency and severity. Wildfire seasons have lengthened in boreal and Mediterranean regions due to warmer, drier conditions, with Landsat data detecting a 15% increase in western U.S. fire frequency since 1984 (Abatzoglou *et al.* 2018). Pest outbreaks are expanding, with bark beetles proliferating in North America and Europe under warming winters (Seidl *et al.* 2017). Cyclones and storms also inflict escalating damage on coastal forests, disrupting regeneration and accelerating carbon losses. Post-disturbance recovery faces mounting challenges. Seed scarcity, invasive species competition, and altered soil-water dynamics hinder regeneration, pushing ecosystems

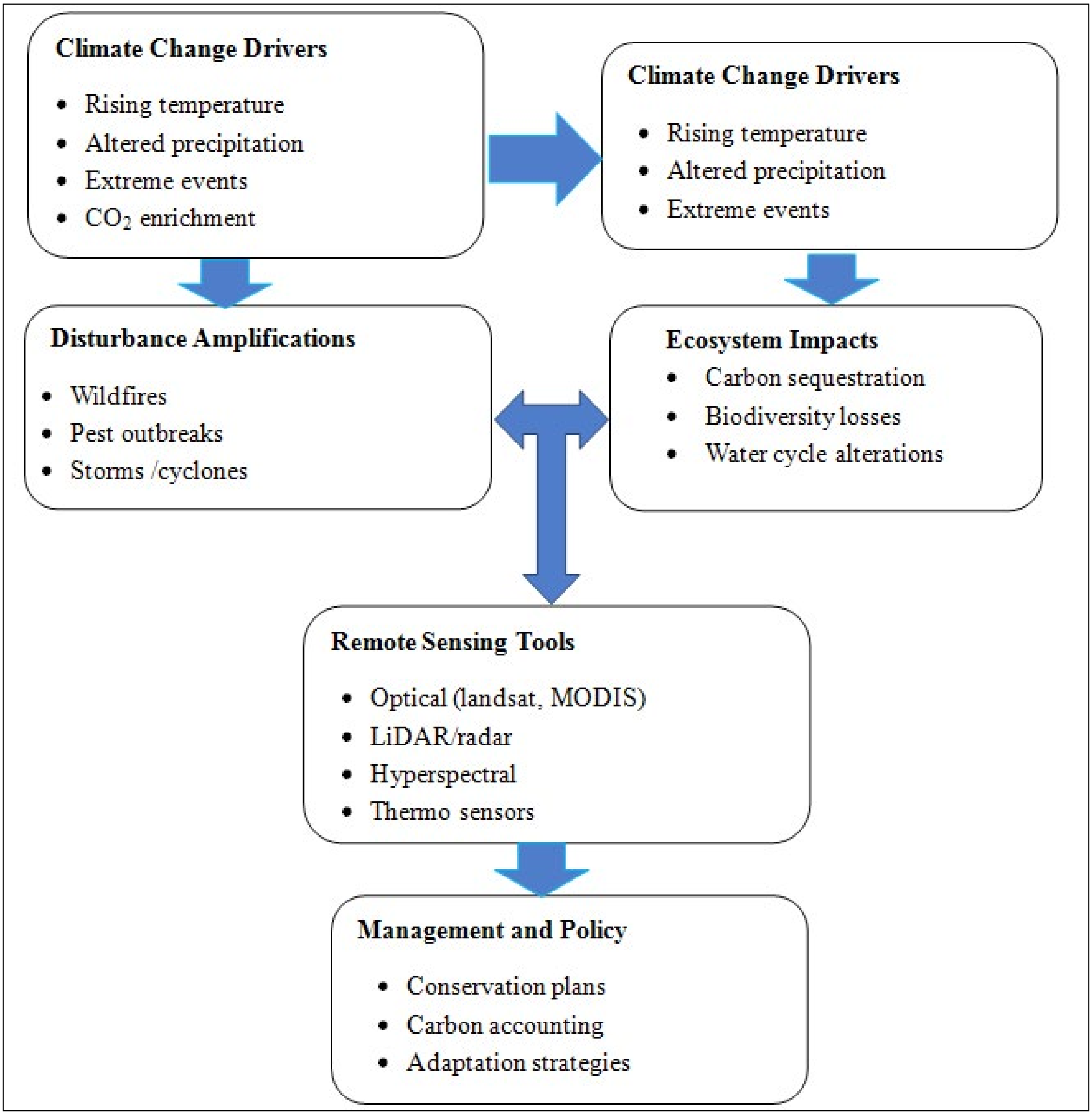

Fig. 1: Forest dynamics under climate change

toward alternative stable states like grasslands (Johnstone *et al*. 2016). Remote sensing confirms slowing recovery trajectories under recurrent disturbances, indicating eroded resilience (Pugh *et al*. 2019). Remote sensing technology has become indispensable for monitoring these dynamics. Satellite-derived NDVI tracks phenological shifts, revealing earlier springs and delayed autumns (Jeong *et al*. 2013). LiDAR and radar quantify structural changes like biomass loss from drought or pests (Baccini *et al*. 2017). However, limitations persist in detecting sub-canopy processes and species-specific responses, necessitating integration with ground data (Schimel *et al*. 2015). Future advancements in hyperspectral imaging and AI-driven analytics promise enhanced resolution of physiological stressors (chlorophyll fluorescence) and carbon fluxes.

REMOTE SENSING TECHNOLOGIES IN FOREST MONITORING

Remote sensing technologies have become indispensable for monitoring forest dynamics under climate change, offering multi-scale insights into vegetation cover, structure, and health that cannot be captured solely through field-based surveys. Satellite-based optical sensors provide long-term, consistent records of forest change, with programs like Landsat, Sentinel-2, and MODIS delivering critical data on forest cover, canopy greenness, and phenological patterns at regional to global scales (Wulder *et al*. 2020). Landsat's five-decade archive enables detection of deforestation and degradation trends, while Sentinel-2's higher resolution enhances monitoring of finer-scale disturbances (Drusch *et al*. 2012; Sairam *et al*. 2023, 2025). MODIS's daily revisit time tracks large-scale vegetation dynamics and seasonal productivity shifts, revealing climate-induced advances in growing seasons (Zhang *et al*. 2003; Jeong *et al*. 2013). Active remote sensing technologies overcome limitations of optical systems. Radar-based Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR) penetrate cloud cover and canopy layers, providing structural, moisture, and biomass data crucial for carbon stock monitoring in tropical regions (Santoro and Cartus, 2023). Sentinel-1's C-band radar identifies moisture stress linked to tree mortality in boreal forests, while InSAR measures subtle vertical canopy changes for biomass estimation (Bouvet *et al*. 2018; Solberg *et al*. 2013). Light Detection and Ranging (LiDAR) delivers highly accurate 3D measurements of canopy structure and biomass distribution. Airborne LiDAR quantifies carbon stocks and storm damage at fine resolutions, while spaceborne missions like NASA's GEDI provide unprecedented global data on vertical structure, enabling modeling of carbon dynamics under climate change (Dubayah *et al*. 2010).

At finer scales, unmanned aerial vehicles (UAVs) equipped with optical, multispectral, or LiDAR sensors capture high-resolution imagery for species identification, health assessments, and post-disturbance recovery analysis (Paneque-Gálvez *et al*. 2014). Thermal sensors (ECOSTRESS) and hyperspectral imaging (PRISMA) add physiological dimensions by tracking canopy temperature and biochemical traits. ECOSTRESS data reveal water stress during heatwaves, while hyperspectral sensors detect chlorophyll fluorescence and nitrogen content, offering early warnings of nutrient limitations (Fisher *et al*. 2020). Despite advances, challenges persist. Coarse-resolution sensors (MODIS) miss small-scale disturbances, while LiDAR and hyperspectral data face spatiotemporal coverage gaps (Wulder *et al*. 2020). Distinguishing climate-driven changes from anthropogenic activities (logging) requires integrated ground-truthing and AI-driven analytics (Schimel *et al*. 2015). Cloud cover in tropics and signal saturation in dense canopies further limit accuracy. Future directions emphasize multi-sensor fusion (combining Sentinel-1, Sentinel-2, and GEDI) and AI algorithms like convolutional neural networks for real-time disturbance detection. Upcoming missions such as NASA's NISAR and ESA's BIOMASS will enhance global biomass and structural monitoring, enabling predictive modeling of forest resilience under climate scenarios (Le Toan *et al*. 2021). These integrated approaches are critical for informing conservation strategies, carbon accounting, and policy frameworks.

ADVANCED APPROACHES AND INTEGRATION

The integration of multi-sensor remote sensing data with advanced analytical techniques represents a paradigm shift in monitoring forest dynamics under climate change. Traditional single-sensor approaches fail to capture the complexity of climate-driven processes, necessitating integrated frameworks that leverage complementary strengths of diverse technologies (Wulder *et al*. 2020). Multi-sensor data fusion combining optical, radar, LiDAR, thermal, and hyperspectral data overcomes individual limitations such as cloud cover (optical), signal saturation (LiDAR), or coarse resolution (MODIS) (Table 1). Hyperspectral imaging, in particular, captures fine spectral signatures across hundreds of narrow bands, enabling detailed characterization of canopy traits, species composition, and physiological stress indicators (chlorophyll decline, water stress) critical for early detection of climate-driven stressors (Asner *et al*. 2017). For instance, fusing Sentinel-1 (radar) and Sentinel-2 (optical) enables cloud-free tropical deforestation monitoring, while integrating GEDI LiDAR with Landsat time-series improves biomass estimates by 30% in structurally complex forests (Reiche *et al*. 2021; Dubayah *et al*. 2010).

Machine learning (ML) and artificial intelligence (AI) transform the analysis of complex remote sensing datasets by automating feature extraction and pattern recognition (Vennela *et al*. 2025). Convolutional neural networks (CNNs) process high-dimensional data to detect subtle disturbances like pest outbreaks or drought stress with >90% accuracy (Wagner *et al*. 2023). Random Forest algorithms and support vector machines (SVMs) integrate multi-temporal data to predict species migration and classify forest types under climate scenarios, outperforming traditional models (Wang *et al*. 2021). Deep learning excels at identifying non-linear relationships in big data, enhancing scalability for global monitoring as demonstrated by Google Earth Engine's near-real-time forest change alerts (Reichstein *et al*. 2019). Coupling remote sensing with ecological and climate models bridges observational data and predictive capacity. Data assimilation techniques integrate satellite-derived metrics (NDVI, biomass, canopy height) into dynamic global vegetation models (DGVMs) and Earth system models (ESMs), improving projections of carbon sequestration, species distribution shifts, and ecosystem resilience under warming scenarios (Thurner *et al*. 2019; Bonan & Doney, 2018). UAV-collected hyperspectral data further calibrated eddy covariance tower measurements, refining water and carbon flux estimates (Rocchini *et al*. 2021). This integration enables "digital twin" simulations to test interventions like assisted migration or fire management before field implementation (Schulze *et al*. 2022; Anderegg *et al*. 2020).

Table 1: Advanced approaches and integration, key technologies, primary benefits, and challenges.

Approach	Key Technologies	Primary Benefits	Notable Examples	Key Challenges
Multi-Sensor Data Fusion	Optical, Radar, LiDAR, Thermal, Hyperspectral	Overcomes individual sensor limitations; comprehensive monitoring across conditions.	Sentinel-1/2 fusion (cloud-free deforestation); GEDI + Landsat (30% biomass accuracy)	Data harmonization; varying resolutions/wavelengths; signal saturation in dense canopies
Machine Learning & AI	CNNs, Random Forests, SVMs, Deep Learning	Automates feature extraction; detects subtle patterns; high accuracy (>90%); scalability	CNNs for pest/ drought detection; Google Earth Engine for real-time alerts	Large training data requirements, computational demands, and limited accessibility in developing regions
Model Coupling	DGVMs, ESMs, Data Assimilation, Digital Twins	Bridges the observation-prediction gap; improves climate projections; tests interventions	UAV hyperspectral + eddy covariance; LPJ-GUESS with NDVI/ biomass data	Model complexity; calibration needs; integrating multi-source data streams
Future Directions	Open-data initiatives, Cloud computing, and Explainable AI	Enhanced transparency; improved accessibility; real-time decision support	NASA's MAIA: Explainable AI frameworks	Ethical AI implementation; equitable data access; computational infrastructure gaps

Despite progress, challenges persist. Data harmonization across sensors with varying resolutions, wavelengths, and acquisition times remains complex (Asner *et al*. 2017). ML models require extensive training datasets, which are scarce for understudied regions like tropical Africa. Computational demands for processing big data limit accessibility, particularly for developing nations (Schimel *et al*. 2015). Future advancements hinge on open-data initiatives (NASA's MAIA), cloud computing, and explainable AI to ensure transparency in climate-related decision-making (Reiche *et al*. 2021). Together, these integrated approaches enhance detection of ecosystem responses and predictive assessments of forest dynamics, providing critical insights for conservation, restoration, and climate adaptation strategies under global initiatives like REDD+.

CASE STUDIES AND REGIONAL APPLICATIONS

The application of remote sensing technologies in forest monitoring has generated valuable insights across diverse ecological regions, each facing unique climate-driven challenges. Tropical forests, particularly in the Amazon, Congo Basin, and Southeast Asia, are among the most intensively studied due to their global importance in biodiversity and carbon cycling (Table 2). Climate change interacts with deforestation, fragmentation, and fire dynamics to accelerate forest degradation in these regions. For instance, satellite-based monitoring with Landsat and MODIS has revealed large-scale deforestation and increasing fire frequency in the Amazon, threatening its capacity as a carbon sink (Aragão *et al*. 2018). Similarly, radar and LiDAR observations in the Congo Basin have been instrumental in quantifying aboveground biomass and detecting selective logging, highlighting the role of intact tropical forests in climate regulation (Baccini *et al*. 2012). In Southeast Asia, hyperspectral and drone-based monitoring has been applied to track oil palm expansion and peatland degradation, demonstrating the value of high-resolution tools for capturing fine-scale land-use change (Miettinen *et al*. 2016). In contrast, boreal forests are increasingly vulnerable to warming temperatures and permafrost thaw, which alter fire regimes, soil hydrology, and carbon storage. Remote sensing has been essential in detecting these shifts. For example, time-series analyses from MODIS and Sentinel data have documented lengthening growing seasons and shifts in vegetation phenology across Siberia and Canada (Ju and Masek, 2016). LiDAR and radar-based approaches have provided crucial measurements of forest structure and permafrost subsidence, enabling the detection of thermokarst features and their influence on forest regeneration (Jones *et al*. 2011). Fire disturbance, a dominant driver of boreal forest dynamics, is increasingly monitored with thermal and optical satellites, allowing for improved assessment of fire frequency, intensity, and post-fire recovery (Kasischke & Turetsky, 2006). Such data highlight the sensitivity of boreal ecosystems to even small temperature increases, with implications for the release of vast carbon stocks stored in frozen soils.

African and Asian drylands present another critical frontier for forest-climate research, as these ecosystems are highly susceptible to desertification, land degradation, and prolonged droughts. Remote sensing provides cost-effective tools for monitoring vegetation cover, land degradation, and recovery in these resource-constrained regions. In the Sahel, long-term NDVI datasets from AVHRR and MODIS have been used to detect "greening" trends linked to increased rainfall variability and land management interventions (Herrmann and Tappan, 2013). In East Africa, UAVs and Sentinel imagery have been applied to map agroforestry systems and assess the role of woody vegetation in enhancing resilience to drought (Brandt *et al*. 2017; Maitra et al. 2024b, 2025b). Similarly, in South and Central Asia, SAR and optical time series have been employed to track desertification processes and shifts in tree cover in arid landscapes, providing crucial inputs for restoration initiatives under the UN Convention to Combat Desertification (Wen *et al*. 2020). These regional case studies illustrate the versatility of remote sensing tools in addressing climate-driven forest dynamics across contrasting biomes. From monitoring large-scale deforestation in the humid tropics, to detecting thaw-related disturbances in boreal forests, to tracking vegetation loss and recovery in drylands, remote sensing has become indispensable for identifying both vulnerabilities and opportunities for resilience. Importantly, these applications highlight the need for regionally

Table 2: Case studies and regional applications, and the remote sensing tools

Region	Climate-driven challenges	Remote sensing tools	Applications	References
Tropical Forests (Amazon, Congo, Southeast Asia)	Deforestation, fragmentation, fire dynamics, and peatland degradation	Landsat, MODIS, Radar, LiDAR, Hyperspectral, UAVs	- Deforestation and fire frequency in the Amazon - Biomass quantification and selective logging in Congo - Oil palm expansion and peatland degradation in SE Asia	Aragão *et al*. 2018; Baccini *et al*. 2012; Miettinen *et al*. 2016
Boreal Forests (Siberia, Canada, Alaska)	Warming, permafrost thaw, altered fire regimes, and hydrology shifts	MODIS, Sentinel, LiDAR, Radar, Thermal satellites	- Lengthening growing seasons and phenology shifts - Detection of permafrost subsidence and thermokarst - Monitoring fire frequency, intensity, and recovery	Ju and Masek, 2016; Jones *et al*. 2011; Kasischke and Turetsky, 2006
African Drylands (Sahel, East Africa)	Desertification, drought, and land degradation	AVHRR, MODIS, UAVs, Sentinel	- NDVI shows "greening" linked to rainfall and management - Mapping agroforestry and woody cover for drought resilience	Herrmann and Tappan, 2013; Brandt *et al*. 2017
Asian Drylands (South and Central Asia)	Desertification, prolonged drought, vegetation loss	SAR, Optical time series	- Tracking desertification processes - Monitoring shifts in tree cover and supporting restoration programs	Wen *et al*. 2020

tailored approaches that combine multi-sensor datasets, ecological modeling, and ground-based validation to guide sustainable forest management and climate adaptation strategies globally.

Challenges and Limitations

Despite the rapid progress in remote sensing technologies, several challenges continue to constrain their effective application in monitoring forest dynamics under climate change. A major obstacle is cloud cover and atmospheric interference, which often limit the usability of optical satellite imagery in tropical regions where persistent cloudiness prevails. Sensors such as MODIS and Landsat frequently encounter data gaps due to atmospheric obstructions, reducing temporal consistency and complicating long-term monitoring (Zhu & Woodcock, 2014). Although radar systems like Synthetic Aperture Radar (SAR) can penetrate clouds, their interpretation is complex and requires specialized expertise, particularly in dense forest environments (Santoro & Cartus, 2023). Another critical issue involves scaling and resolution mismatches between different sensors and ecological processes. For example, coarse-resolution products such as MODIS provide valuable global coverage but may fail to capture fine-scale disturbances like selective logging or localized pest outbreaks (Hansen *et al*. 2013). Conversely, very high-resolution data from UAVs or commercial satellites allow detailed analysis at local levels but are difficult to integrate with large-scale climate models due to differences in spatial and temporal resolution (Wu *et al*. 2019). This scaling problem often leads to uncertainties when attempting to link remote sensing observations with ecological processes and policy-relevant carbon accounting frameworks.

The high costs and limited accessibility of advanced technologies further hinder widespread adoption, particularly in developing regions where forest monitoring is most urgently needed. Airborne LiDAR surveys and high-resolution commercial satellite imagery, for instance, remain prohibitively expensive for many research institutions and government agencies in the Global South (Kellndorfer *et al*. 2010). While open-access programs like Landsat, Sentinel, and GEDI have significantly expanded data availability, financial and technical barriers continue to limit their integration into national forest monitoring systems (Herold &

Table 3: Future perspectives and policy implications

Focus Area	**Strategies**	**Key contributions**	**References**
Emerging spaceborne technologies	◆ CubeSats (Planet Labs) ◆ GEDI (Global Ecosystem Dynamics Investigation) - ICESat-2	◆ Near-daily high-resolution imagery for disturbance monitoring - 3D measurements of canopy height, structure, biomass - Improved accuracy in global carbon stock assessments	Houborg and McCabe, 2018; Dubayah *et al.* 2010; Neuenschwander and Pitts, 2019
Long-term monitoring networks and open data	◆ Landsat archive ◆ Copernicus Sentinel program - FAO Global Forest Resources Assessment	◆ Freely accessible harmonized datasets ◆ Supports calibration with ground inventories ◆ Strengthens continuity in climate-driven monitoring	Wulder *et al.* 2020
Policy frameworks (global and national)	◆ REDD + under UNFCCC ◆ Climate finance mechanisms	◆ Satellite-based biomass and carbon accounting ◆ Verifiable evidence for performance-based payments ◆ Informs national sustainable land-use strategies	Herold and Johns, 2007; Goetz *et al.* 2015
Community-based Forest management	◆ Participatory monitoring (drones, smartphones, GIS) - Local data collection programs	◆ Complements large-scale satellite data ◆ Improves ground-truthing and data quality ◆ Empowers communities, enhances social and ecological resilience	Brofeldt *et al.* 2014

Johns, 2007). Finally, there is a persistent need for ground-truth validation to ensure the accuracy of remotely sensed estimates. Remote sensing models of biomass, canopy cover, or species composition require calibration with field data to minimize errors and improve predictive reliability (Foody, 2015). However, the collection of such data is often logistically challenging, especially in remote or politically unstable regions. Limited availability of long-term ecological plots further constrains the ability to validate large-scale forest dynamics derived from satellite or airborne sensors. These challenges underscore the importance of adopting interdisciplinary approaches that combine multi-sensor data fusion, improved algorithms, and expanded field networks. Bridging these gaps is essential not only for advancing scientific understanding of climate-driven forest change but also for supporting robust decision-making in conservation, restoration, and climate policy frameworks.

Future perspectives and policy implications

The future of monitoring forest dynamics under climate change lies in the integration of emerging remote sensing technologies with global policy frameworks and local management strategies. New spaceborne missions are transforming data availability and resolution. CubeSats, operated by private companies such as Planet Labs, provide near-daily high-resolution imagery, enabling continuous monitoring of forest disturbances at unprecedented scales (Houborg and McCabe, 2018). Similarly, NASA's Global Ecosystem Dynamics Investigation (GEDI) and ICESat-2 missions deliver critical advances in three-dimensional measurements of forest canopy height, structure, and aboveground biomass, improving carbon stock assessments essential for climate change mitigation efforts (Dubayah *et al.* 2010; Neuenschwander & Pitts, 2019). These developments are expected to significantly reduce uncertainties in global forest carbon budgets and enhance the accuracy of land-based mitigation targets. Equally important is the establishment of long-term monitoring networks and open-access data platforms, which allow scientists, policymakers, and local communities to access harmonized and comparable forest datasets. Open initiatives such as the Landsat archive, Copernicus Sentinel program, and FAO's Global Forest Resources Assessment have already transformed global monitoring by making high-quality data freely available (Wulder *et al*. 2020). Linking these efforts with national forest inventories and ground-based ecological networks ensures continuity, calibration, and validation across spatial and temporal scales, a crucial step in addressing climate-driven forest changes.

Remote sensing technologies also play a central role in supporting international policy frameworks, particularly REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and related climate agreements under the UNFCCC (Table 3). High-resolution satellite data and biomass estimates provide verifiable evidence for carbon accounting, enabling countries to receive performance-based payments for avoided deforestation and forest restoration (Herold & Johns, 2007; Goetz *et al*. 2015). This integration strengthens transparency and trust in climate finance mechanisms, while also guiding national strategies on sustainable land management. Finally, the integration of technology with community-based forest management offers a pathway to enhance both ecological and social resilience. Participatory forest monitoring programs, where local communities use smartphones, drones, or simplified GIS platforms, can complement large-scale satellite systems by providing fine-scale ground data (Brofeldt *et al*. 2014). Such approaches not only improve data quality but also empower local stakeholders to engage directly in conservation and climate mitigation, creating co-benefits for livelihoods and biodiversity. Looking ahead, the convergence of advanced technologies, open-access platforms, and participatory governance will be central to addressing the dual challenges of climate change and forest degradation. By bridging global monitoring systems with local action, remote sensing can serve not only as a scientific tool but also as a critical enabler of climate policy, sustainable development, and community empowerment.

CONCLUSION

Remote sensing has emerged as an indispensable tool for understanding and managing forest dynamics in the face of climate change. By providing multi-scale, continuous, and non-invasive measurements of forest structure, biomass, phenology, and disturbance regimes, remote sensing technologies have revolutionized the way researchers and policymakers assess ecosystem responses to climate variability. Traditional optical sensors such as Landsat and Sentinel offer critical long-term records of canopy cover and land-use change, while radar and LiDAR systems provide structural information that enhances estimates of aboveground biomass and carbon storage. Recent advancements, including hyperspectral imaging, CubeSats, and UAV-based approaches, have further improved the ability to detect subtle ecological changes, monitor localized disturbances, and map species-level variability with unprecedented accuracy.

The integration of remote sensing with advanced computational techniques such as machine learning, artificial intelligence, and ecological modeling has also opened new pathways for predictive monitoring. These methods enable the detection of early-warning signals of forest stress, the anticipation of large-scale disturbances such as fires and pest outbreaks, and the refinement of climate–vegetation interaction models. Furthermore, the alignment of remote sensing capabilities with global policy frameworks such as REDD+ has positioned these technologies as vital components of climate change mitigation, providing transparent, verifiable, and scalable data for carbon accounting and forest conservation strategies. Despite these achievements, challenges remain. Persistent cloud cover in tropical regions, mismatches in spatial and temporal resolution, and the scarcity of reliable ground-truth data continue to limit the accuracy and applicability of remote sensing products. High operational costs and limited access to cutting-edge technologies further constrain uptake in many developing countries, where forests are often most vulnerable to climate impacts. Addressing these barriers requires interdisciplinary collaboration, investment in open-access datasets, and the establishment of long-term ecological monitoring networks that integrate both remote sensing and in-situ measurements. Looking ahead, strengthening forest–climate resilience will depend on leveraging emerging technologies such as GEDI, ICESat-2, and CubeSats, while ensuring that their outputs are linked to community-based monitoring and participatory management systems. By coupling global-scale satellite observations with local ecological knowledge and adaptive management practices, remote sensing can bridge science, policy, and practice, ultimately guiding effective strategies for biodiversity conservation, sustainable forest use, and climate adaptation. In sum, remote sensing not only advances scientific understanding of forest-climate interactions but also provides the practical tools needed to safeguard forests as critical regulators of the Earth's climate system.

REFERENCES

Abatzoglou, J.T., Williams, A.P., Boschetti, L., Zubkova, M. and Kolden, C.A. 2018. Global patterns of interannual climate–fire relationships. *Global Change Biol.*, **24**(11):5164–5175.

Ainsworth, E.A. and Long, S.P. 2021. 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? *Global Change Biol.*, **27**(1): 27–49.

Anderegg, W.R., Trugman, A.T., Badgley, G., Anderson, C.M., Bartuska, A., Ciais, P. and Randerson, J.T. 2020. Climate-driven risks to the climate mitigation potential of forests. *Science*, **368**(6497): eaaz7005.

Aragão, L.E., Anderson, L.O., Fonseca, M.G., Rosan, T.M., Vedovato, L.B., Wagner, F.H. and Saatchi, S. 2018. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat. Comm.*, **9**(1): 536.

Asner, G.P., Martin, R.E., Anderson, C.B., Kryston, K., Vaughn, N., Knapp, D.E. and Field, C.B. 2017. Scale dependence of canopy trait distributions along a tropical forest elevation gradient. *New Phytol.*, **214**(3): 973–988.

Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D. and Houghton, R.A. 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Chang.*, **2**(3): 182–185.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D. and Houghton, R.A. 2017. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*, **358**(6360): 230–234.

Boisvert-Marsh, L., Périé, C. and de Blois, S. 2019. Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. *Ecosphere*, **10**(3): e02672.

Bonan, G.B. and Doney, S.C. 2018. Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. *Science*, **359**(6375): eaam8328.

Bouvet, A., Mermoz, S., Ballère, M., Koleck, T. and Le Toan, T. 2018. Use of the SAR shadowing effect for deforestation detection with Sentinel-1 time series. *Remote Sens.*, **10**(8): 1250.

Brandt, M., Rasmussen, K., Peñuelas, J., Tian, F., Schurgers, G., Verger, A. and Fensholt, R. 2017. Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nat. Ecol. Evol.*, **1**(4): 0081.

Brofeldt, S., Theilade, I., Burgess, N.D., Danielsen, F., Poulsen, M.K., Adrian, T. and Widayati, A. 2014. Community monitoring of carbon stocks for REDD+: Does accuracy and cost change over time? *Forests*, **5**(8): 1834–1854.

Chappa, L.R., Nungula, E.Z., Makwinja, Y.H., Ranjan, S., Sow, S., Alnemari, A.M., Maitra, S., Seleiman, M.F., Mwadalu, R. and Gitari, H.I. 2024. Outlooks on Major Agroforestry Systems. *In:* Raj A, Jhariya MK, Banerjee A, Jha RK, Singh KP (Eds). Agroforestry. Wiley-Scrivener, USA., pp. 21–48.

Cheptoek, R.P., Mochoge, B., Kisaka, O.M., Otieno, E., Maitra, S., Nasar, J. and Seleiman, M.F. 2021. Maize productivity, economic returns, and phosphorus use efficiency as influenced by lime, Minjingu Rock Phosphate, and NPK inorganic fertilizer. *Int. J. Biores. Sci.*, **8**: 47–60.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F. and Bargellini, P. 2012. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sens. Environ.*, **120**: 25–36.

Dubayah, R.O., Sheldon, S.L., Clark, D.B., Hofton, M.A., Blair, J.B., Hurtt, G.C. and Chazdon, R.L. 2010. Estimation of tropical forest height and biomass dynamics using LiDAR remote sensing at La Selva, Costa Rica. *J. Geophys. Res. Biogeosci.*, **115**(G2).

Emmanuely, N.Z., Chappa, L.R., Ngaiza, V.V., Saeed, A., Ranjan, S., Sow, S., Mwadalu, R., Raza, M.A., Soratto, R.P., Rezaei-Chiyaneh, E. and Nasar, J. 2025. Agroforestry for Monetising Carbon Credits. *In:* Raj A, Jhariya MK, Meena RS (Eds). Carbon trading in Agroforestry under changing climate. Springer, Cham, pp. 89–111.

Emmanuely, N.Z., Chappa, L.R., Ranjan, S., Sow, S., Alnemari, A.M., Seleiman, M.F., Mwadalu, R. and Maitra S. 2024. Ecosystem Services through Agroforestry Systems and its Sustainability. *In:* Raj A, Jhariya MK, Banerjee A, Jha RK, Singh KP (Eds). Agroforestry. Wiley-Scrivener, USA. pp. 223–254.

Fisher, J.B., Lee, B., Purdy, A.J., Halverson, G.H., Dohlen, M.B., Cawse-Nicholson, K. and Hook, S. 2020. ECOSTRESS: NASA's next-generation mission to measure evapotranspiration from the International Space Station. *Water Res. Res.*, **56**(4): e2019WR026058.

Foody, G.M. 2015. Valuing map validation: The need for rigorous land cover map accuracy assessment in economic valuations of ecosystem services. *Ecol. Econ.*, **111**: 23–28.

Gitari, H.I., Nungula, E.Z., Chappa, L.R., Raza, M.A., Ranjan, S., Sow, S., Alnemari, A.M., Seleiman, M.F., Mwadalu, R. and Maitra, S. 2024. Agroforestry for Climate Security. *In:* Raj, A., Jhariya, M.K., Banerjee, A., Jha, R.K., Singh, K.P. (Eds). Agroforestry. Wiley-Scrivener, USA., pp. 319–344.

Goetz, S., Hansen, M., Houghton, R., Walker, W., Laporte, N.T. and Busch, J. 2015. Measurement and monitoring for REDD+: the needs, current technological capabilities and future potential. *Center for Global Development Working Paper*, (392), available online: Measurement and Monitoring for REDD+: The Needs, Current Technological Capabilities and Future Potential

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A. and Townshend, J.R. 2013. High-resolution global maps of 21st-century forest cover change. *Science*, **342**(6160): 850–853.

Herold, M. and Johns, T. 2007. Linking requirements with capabilities for deforestation monitoring in the context of the UNFCCC-REDD process. *Environ. Res. Lett.*, **2**(4): 045025.

Herrmann, S.M. and Tappan, G.G. 2013. Vegetation impoverishment despite greening: A case study from central Senegal. *J. Arid Environ*., **90**: 55–66.

Houborg, R. and McCabe, M.F. 2018. Daily retrieval of NDVI and LAI at 3 m resolution via the fusion of CubeSat, Landsat and MODIS data. *Remote Sens*., **10**(6): 890.

Hubau, W., Lewis, S.L., Phillips, O.L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A. and Zemagho, L. 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, **579**(7797): 80–87.

Jeong, S.J., Ho, C.H., Choi, S.D., Kim, J., Lee, E.J. and Gim, H.J. 2013. Satellite data-based phenological evaluation of the nationwide reforestation of South Korea. *PLoS One*, **8**(3): e58900.

Johnstone, J.F., Allen, C.D., Franklin, J.F., Frelich, L.E., Harvey, B.J., Higuera, P.E. and Turner, M.G. 2016. Changing disturbance regimes, ecological memory and forest resilience. *Front. Ecol. Environ*., **14**(7): 369–378.

Jones, B.M., Grosse, G.D.A.C., Arp, C.D., Jones, M.C., Walter Anthony, K.M. and Romanovsky, V.E. 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *J. Geophys. Res.: Biogeosci*., **116**(G2).

Ju, J. and Masek, J.G. 2016. The vegetation greenness trend in Canada and US Alaska from 1984–2012 Landsat data. *Remote Sens. Environ*., **176**: 1–16.

Kasischke, E.S. and Turetsky, M.R. 2006. Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophys. Res. Lett*., **33**: L09703.

Kellndorfer, J.M., Walker, W.S., LaPoint, E., Kirsch, K., Bishop, J. and Fiske, G. 2010. Statistical fusion of Lidar, InSAR, and optical remote sensing data for forest stand height characterization: A regional-scale method based on LVIS, SRTM, Landsat ETM+, and ancillary data sets. *J Geophysic. Res.: Biogeosc*., **115**(G2).

Le Toan, T., Huu, N., Simioni, M., Phan, H., Arai, H., Mermoz, S. and Espagne, E. 2021. Agriculture in Viet Nam under the impact of climate change. Climate change in Viet Nam. Impacts and adaptation. A COP26 assessment report of the GEMMES Viet Nam project.

Luciana, C.R., Nungula, E.Z., Ngaiza, V.V., Mwadalu, R., Makwinja, Y.H., Dlamini, J.C., Ranjan, S., Sow, S., Raza, M.A., Soratto, R.P. and Raj, A. 2025. The challenges and solutions for carbon credits. *In:* Raj, A., Jhariya, M.K., Meena, R.S. (Eds). Carbon trading in Agroforestry under changing climate. Springer, Cham., pp. 525–549.

Maitra, S., Bhattacharya, U,, Pramanick, B., Sagar, L,, Gaikward, D.J., Pramanick, B., Sairam, M., Sahoo, U., Jatav, H.S., Shankar, T., Kandileri, A.M., Rezaei-Chiyaneh, E. and Hossain, A. 2024a. Agroforestry: A Resource Conserving Technology for Efficient Utilization of Agricultural Inputs, Leads to Food and Environmental Security. *In:* Jatav, H.S., Rajput, V.D., Minkina, T., Van Hullebusch, E.D., Dutta, A. (Eds) Agroforestry to Combat Global Challenges. Sustainable Development and Biodiversity, pp. 15–52. Springer, Singapore.

Maitra, S., Ray, S., Sagar, L., Sairam, M., Pramanick, B., Gitari, H., Santosh, D.T., Jagannath, G.D., Atapattu, A. and Chappa, L.R. 2025a. Cropping System Approach in Climate-Resilient Food Crop Production. In: *Climate-Smart Agricultural Technologies* Springer, Singapore, pp. 327-356. https://doi.org/10.1007/978-981-96-7699-6_15

Maitra, S., Panda, P., Panda, S.K., Behera, D., Shankar, T. and Nanda, S.P. 2020. Relevance of barnyard millet (*Echinochloa frumentacea* L.) cultivation and agronomic management for production sustainability. *Int. J. Bioinform. Biol. Sci*., **8**: 27-32.

Maitra, S., Sairam, M., Ray, S., Santosh, D. T., Gaikwad, D. J., Gitari, H., Mukesh, G. and Maheswari, N. 2024b. Applauding soil quality improvement through legume-based intercropping system: A review. *Int. J. Biores. Sci*., **11**: 59-69.

Maitra, S., Sairam, M., Sagar, L., Ray, S., Santosh, D.T., Gaikwad, D.J., Atapattu, A.J. and Gitari, H.I. (2025b). Alley Cropping: A Sustainable Agroforestry System for Enhancing Productivity, Soil Health and Biodiversity. In *Plant Biotechnology and Sustainable Agriculture: Bridging the Gap for Global Food Security*, CABI, pp. 235-248.

Maitra, S., Santosh, D.T., Jena, J., Berera, S.D., Ray, S., Sairam, M., Palai, J.B., Gaikwad, D.J., Rishitha, S., Atapattu, A.J. and Hossain, A. 2026. Understanding Plant Responses to Abiotic Stress through Systems Biology. *In:* Aftab, T. (Ed). Systems Biology in Crop Improvement: Emerging Tools and Technologies. Elsevier, Chapter 3, pp. 1–33.

Manasa, P., Sairam, M. and Maitra, S. 2021. Influence of maize-legume intercropping system on growth and productivity of crops. *Int. J. Biores. Sci*., **08**(01): 21-28.

Masina, S., Maitra, S., Sahoo, U., Sagar, L. and Krishna, T.G. 2023. Evaluation of precision nutrient tools and nutrient optimization in maize (*Zea mays* L.) for enhancement of growth, productivity and nutrient use efficiency. *Res. Crop*., **24**(4): 666-677.

Miettinen, J., Shi, C. and Liew, S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecol. Conserv*., **6**: 67–78.

Mukesh, G., Sairam, M., Maitra, S., Gaikwad, D.J., Sagar, L. and Ray, S. 2024. Agrometeorological indices, physiological growth parameters and performance of finger millet as influenced by different cultivars under hot and sub-humid region of Odisha. *Int. J. Exp. Res. Rev.*, **42**: 148-161.

Mwadalu, R., Abdi, A.M., Rutto, M., Chappa, L.R., Nungula, E.Z., Rezaei-Chiyaneh, E., Nasar, J., Heydarzadeh, S., Ranjan, S., Sow, S., Dlamini, J.C. and Raj, A. 2025. Potential of agroforestry for enhancing Africa's access to carbon markets: A review. *In*: Raj, A., Jhariya, M.K., Meena, R.S.

(Eds). Carbon trading in Agroforestry under changing climate. Springer, Cham, pp. 325–367.

Neuenschwander, A. and Pitts, K. 2019. The ATL08 land and vegetation product for the ICESat-2 Mission. *Remote Sens. Environ.*, **221**: 247–259.

Nungula, E.Z., Chappa, L.R., Ngaiza, V.V., Msangi, G.S., Dlamini, J.C., Saeed, A., Mwadalu, R., Soratto, R.P., Rezaei-Chiyaneh. E. and Nasar, J. 2025. Climate Change and Carbon Emission Trading. *In:* Raj A, Jhariya MK, Meena RS (Eds). Carbon trading in Agroforestry under changing climate. Springer, Cham., pp. 23–57.

Nungula, E.Z., Mugwe, J., Nasar, J., Massawe, H.J., Karuma, A.N., Maitra, S., Seleiman, M.F., Dindaroglu, T. and Khan, N. 2023. Land degradation unmasked as the key constraint in sunflower (*Helianthus annus*) production: Role of GIS in Revitalizing this vital sector. *Cogent Food Agric.*, **9**(2): 2267863.

Nyawade, S., Karanja, N.N., Gachene, C.K.K., Schulte-Geldermann, E. and Parker, M. 2021. Yield and evapotranspiration characteristics of potato-legume intercropping simulated using a dual coefficient approach in a tropical highland. *Field Crops Res.*, **274**: 108327.

Paneque-Gálvez, J., McCall, M.K., Napoletano, B.M., Wich, S.A. and Koh, L.P. 2014. Small drones for community-based forest monitoring: An assessment of their feasibility and potential in tropical areas. *Forests*, **5**(6): 1481–1507.

Pugh, T.A., Lindeskog, M., Smith, B., Poulter, B., Arneth, A., Haverd, V. and Calle, L. 2019. Role of forest regrowth in global carbon sink dynamics. *Proc. Nat. Acad. Sci.*, **116**(10): 4382–4387.

Raj, A., Jhariya, M.K., Banerjee, A., Mina, H.K. and Mina, K.K. 2025. Carbon Credits in Agroforestry for Net Zero Emissions: A Global Synthesis. *In:* Raj A, Jhariya MK, Meena RS (Eds). Carbon trading in Agroforestry under changing climate. Springer, Cham., pp. 113–127.

Ray, S., Maitra, S., Sairam, M., Sravya, M., Priyadarshini, A., Shubhadarshi, S. and Padhi, D.P. 2024. An unravelled potential of foliar application of micro and beneficial nutrients in cereals for ensuring food and nutritional security. *Int. J. Exp. Res. Rev.*, **41** (Spl. Vol.): 19–42.

Reiche, J., Mullissa, A., Slagter, B., Gou, Y., Tsendbazar, N.E., Odongo-Braun, C. and Herold, M. 2021. Forest disturbance alerts for the Congo Basin using Sentinel-1. *Environ. Res. Lett.*, **16**(2): 024005.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N. and Prabhat, F. 2019. Deep learning and process understanding for data-driven Earth system science. *Nature*, **566**(7743): 195–204.

Rocchini, D,, Salvatori, N,, Beierkuhnlein, C., Chiarucci, A., De Boissieu, F., Förster, M. and Féret, J.B. 2021. From local spectral species to global spectral communities: A benchmark for ecosystem diversity estimate by remote sensing. *Ecological Informatics*, **61**: 101195.

Sairam, M., Maitra, S., Praharaj, S., Nath, S., Shankar, T., Sahoo, U., Santosh, D.T., Sagar, L., Panda, M., Shanthi Priya, Ashwini, T.R., Gaikwad, D.J., Hossain, A. Pramanick, B., Jatav, H.S., Gitari, H.I. and Aftab, T. 2023. An insight into the consequences of emerging contaminants in soil and water and plant responses. In: Emerging Contaminants and Plants Interactions, Adaptations and Remediation Technologies, Aftab, T. (Ed), pp.1 - 27. https://doi.org/10.1007/978-3-031-22269-6_1

Sairam, M., Maitra, S., Sagar, L., Biswas, T., Bárek, V., Brestic, M. and Hossain, A. 2025. Application of precision nutrient tools for the optimization of fertilizer requirements and assessment of the growth and productivity of maize (*Zea mays* L.) in the northeastern Ghat of India. *J Agric. Food Res.*, **21**: 101958.

Santoro, M. and Cartus, O. 2023. ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the years 2010, 2017, 2018, 2019 and 2020, v4.

Santosh, D.T., Debnath, S., Maitra, S., Sairam, M., Sagar, L.L., Hossain, A. and Moulick, D. 2024. Alleviation of climate catastrophe in agriculture through adoption of climate-smart technologies. *In:* Climate Crisis: Adaptive Approaches and Sustainability. (Eds; Chatterjee, U., Shaw, R., Kumar, S., Raj, A.D. and Das, S.) Springer Nature Switzerland, pp. 307-32. https://doi.org/10.1007/978-3-031-44397-8_17.

Schimel, D., Pavlick, R., Fisher, J.B., Asner, G.P., Saatchi, S., Townsend, P. and Cox, P. 2015. Observing terrestrial ecosystems and the carbon cycle from space. *Global Chang. Biol.*, **21**(5): 1762–1776.

Schulze, E.D., Bouriaud, O., Irslinger, R. and Valentini, R. 2022. The role of wood harvest from sustainably managed forests in the carbon cycle. *Ann. Forest Sci.*, **79**(1): 17.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G. and Reyer, C.P. 2017. Forest disturbances under climate change. *Nat. Clim. Chang.*, **7**(6): 395–402.

Solberg, S., Astrup, R., Breidenbach, J., Nilsen, B. and Weydahl, D. 2013. Monitoring spruce volume and biomass with InSAR data from TanDEM-X. *Remote Sens. Environ.*, **139**: 60–67.

Soratto, R.P., Perdoná, M.J., Parecido, R.J. and Pinotti, R.N. 2022. Turning biennial into biannual harvest: Long-term assessment of Arabica coffee–macadamia intercropping and irrigation synergism by biological and economic indices. *Food Energy Sec.*, **11**(2): e365.

Sow, S., Ranjan, S, Seleiman, M.F., Alkharabsheh, H.M., Kumar, M., Kumar, N., Padhan, S.R., Roy, D.K., Nath, D. and Wasonga, D.O. 2024. Artificial Intelligence for Maximizing Agricultural Input Use Efficiency: Exploring Nutrient, Water and Weed Management Strategies. *Phyton-Int. J. Exper. Bot.*, **93**(7): 1569–1598.

Thurner, M., Beer, C., Crowther, T., Falster, D., Manzoni, S., Prokushkin, A. and Schulze, E.D. (2019). Sapwood biomass carbon in northern boreal and temperate forests. *Global Ecol. Biogeog.*, **28**(5): 640–660.

Vennela, M., Varma, D.D., Sadhu, S., Padhan, S.R and Roy, D.K. (2025). Accelerating Role of Artificial Intelligence and Robotics in Crop Improvement. *In:* Kumar S, Ranjan S, Sow S, Padhan SR, Roy DK (Eds). Climate-Resilient

Agriculture for Sustainable Crop Production. CRC Press, Taylor and Francis Group, pp. 187–208.

Vogt, P., Riitters, K.H., Caudullo, G. and Eckhardt, B. 2019. FAO-State of the World's forests: forest fragmentation. Publications Office of the European Union: Luxembourg.

Wagner, F.H., Dalagnol, R., Silva-Junior, C.H., Carter, G., Ritz, A.L., Hirye, M.C. and Saatchi, S. 2023. Mapping tropical forest cover and deforestation with Planet NICFI satellite images and deep learning in Mato Grosso State (Brazil) from 2015 to 2021. *Remote Sens.*, **15**(2): 521.

Wang, M., Fan, L., Frappart, F., Ciais, P., Sun, R., Liu, Y. and Wigneron, J.P. 2021. An alternative AMSR2 vegetation optical depth for monitoring vegetation at large scales. *Remote Sens. Environ.*, **263**: 112556.

Wen, J., Köhler, P., Duveiller, G., Parazoo, N.C., Magney, T.S., Hooker, G. and Sun, Y. 2020. A framework for harmonizing multiple satellite instruments to generate a long-term global high spatial-resolution solar-induced chlorophyll fluorescence (SIF). *Remote Sens. Environ.*, **239**: 111644.

Wu, Q., Lane, C.R., Li, X., Zhao, K., Zhou, Y., Clinton, N. and Lang, M.W. 2019. Integrating LiDAR data and multi-temporal aerial imagery to map wetland inundation dynamics using Google Earth Engine. *Remote Sens. Environ.*, **228**: 1–13.

Wulder, M.A., Hermosilla, T., Stinson, G., Gougeon, F.A., White, J.C., Hill, D.A. and Smiley, B.P. 2020. Satellite-based time series land cover and change information to map forest area consistent with national and international reporting requirements. *Forestry*: *Int. J. Forest Res.*, **93**(3): 331–343.

Zhang, X., Friedl, M.A., Schaaf, C.B., Strahler, A.H., Hodges, J.C., Gao, F. and Huete, A. 2003. Monitoring vegetation phenology using MODIS. *Remote Sens. Environ.*, **84**(3): 471–475.

Zhu, Z. and Woodcock, C.E. 2014. Continuous change detection and classification of land cover using all available Landsat data. *Remote Sens. Environ*, **144**: 152–171.