Geospatial artificial intelligence for automating forest land encroachment detection in India

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Abstract.=Forest lands in India are under severe pressure from illegal encroachment despite the enactment of the Indian Forest Act(IFA) 1927 and Forest (Conservation) Act (FCA) 1980. This situation effectively reduces the land available for afforestation, affecting India's global commitment to fighting climate change. Encroachment in remote locations goes undetected, preventing any measures for removal. The feasibility of applying Artificial intelligence(AI) methods on Very High Resolution(VHR) satellite imagery to automate the identification of encroachments was examined. The evaluation found that the current level of research makes it feasible. A novel method for detection and monitoring of eviction of encroachment on forestland was proposed to increase the land available for afforestation. This method can ensure more CO_2 sequestration to help India meet its commitments in fighting climate change.

Keywords.=Forest, Conservation, Artificial intelligence, Climate change, Encroachment
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1. Introduction

How the current generation deals with climate change will impact all the generations to come. Thanks to the awareness raised in this regard in the last few decades, the severity of the consequences of climate change and the required mitigation efforts is well known. Yet, in 2021, the world faced the calamitous impacts of climate change ranging from the deaths of countless mussels on beaches of Vancouver (Roxanne Egan-Elliott, 2021) to the unprecedented destructive rainfall in China (Jeff Masters, 2021).

1.1. *India's global commitment*

India's Intended Nationally Determined Contribution (INDC) in response to COP decisions 1/CP.19 and 1/CP.20 for the period 2021 to 2030 consisted of eight decisions which included one related to afforestation (Government of India, 2022). Through afforestation, the creation of an additional carbon sink of 2.5-3 billion tonnes of CO_2 equivalent by 2030 is one of India's INDC (Government of India, 2022).

1.2. *Concerns on impact of forest land encroachment in fighting climate change in 2016*

Due to the increase in people's concern, questions are rising on the efficacy of the climate change mitigation measures, like afforestation on forest land. In the Lok Sabha of the Indian Parliament, such a question was raised in July 2016 by the Member of Parliament Neelam Sonker (Sonker, 2016). Amongst others, the most pertinent question was,

> Will the Minister of Environment, Forest and Climate Change be pleased to state :(a) whether it is a fact that rapid climate change has been taking place in the country due to encroachment on forestland;

(Sonker, 2016). However, the reply to this question stated that

> No study has so far come to the notice of the Ministry regarding rapid climate change in the country due to encroachment on forest land.

, the subsequent questions raised by Neelam Sonker and the answers received need to be analysed (Sonker, 2016).

The other questions raised by Neelam Sonker (Sonker, 2016) were on details of forest land encroachment in India, steps being taken by the Government to check forest encroachment and details of the incentives being given by the Government to increase the forest cover. The answer to the question regarding forest encroachment stated that 1.48 million hectares of forest land are under encroachment (Sonker, 2016). On the question of the government's financial incentives to increase the forest cover, the answer revealed that 3962.6 million Indian Rupees had been spent in 2014-15 & 2015-16 by the government (Sonker, 2016). This expenditure was on three afforestation schemes, namely the National Afforestation Program(NAP), Intensification of Forest Management Scheme(IFMS), and Green India Mission(GIM) (Sonker, 2016).

Now, one may wonder if the climate change mitigation efforts may have been more effective had afforestation been carried out on the 1.48 million hectares of forest land under encroachment.

1.3. India's forests and their carbon sequestration capacity

Forest land available for afforestation is limited. Forest in India is a tract of land legally proclaimed to be one under the Indian Forest Act, 1927 or Forest (Conservation) Act,1980 (Parliamentary Standing Committee, 2019). In India there are three types of legal forests under the Indian Forest Act,1927 (Government of India, 1927): Reserved forests (RF), Protected Forests (PF), and Unclassed Forests (UF)(Parliamentary Standing Committee, 2019). India has a notified forest area of 76.79 million hectares (m ha), comprising 43.47 m ha of Reserved, 21.94 m ha of Protected and 11.38 m ha of Unclassed (unclassified) Forests (Parliamentary Standing Committee, 2019).

Studies have found that planted forests/woodlots have the highest CO_2 removal rates, ranging from 4.5 to 40.7 t CO_2 ha^{-1} $year^{-1}$ during the first 20 years of growth(Bernal et al., 2018). Therefore, additionally, a minimum of 6.66 to a maximum of 60.236 million t CO_2 $year^{-1}$ could have been sequestered for the first 20 years of growth on the 1.48 million hectares of forest land under encroachment. There also exist other concerns on India's efforts to meet its forestry NDC goal of ensuring sequestration of 2.5-3 billion tonnes of CO_2 equivalent through additional afforestation by 2030 (Mathur et al., 2021).

1.4. Dearth of unequivocal answers on forest land encroachment

The concern with which the people of India view encroachment on forest land can be inferred from the frequent questions asked by the people's representatives in the Indian Parliament to the Government of India. Apart from the question on encroachment on forest land raised in the 16th Lok Sabha, questions on the same have been raised by other parliamentarians in the 17th Lok Sabha also, in 2020 (Kaushik and Saikia, 2020), and 2021 (Chand, 2021).

The information on forest land under encroachment provided through the reply to Lok Sabha questions in 2016 (Sonker, 2016), and in 2021 (Chand, 2021) reveals that 13 states/union territories (n=13/31) reported an increase, 15 (n=15/31) reported a decrease, and 8 (n=8/31) reported no change. However, these reports (Sonker, 2016,Chand, 2021) lack detailed information on new encroachments detected in the year and encroachment evicted in the year, due to which a year-on-year dynamic view of combating encroachment cannot be ascertained. These reports (Sonker, 2016,Chand, 2021) are also not providing information on the duration, type of encroachments as well as their numbers, for example, Roads(since 2018)-0.05 million km or Buildings(since 2000) -0.5 million or Buildings(since 1990)-0.8 million or Agricultural fields(since 2003)-0.3 million or Rubber Plantation(since 1998)-0.1 million hectares.

1.5. Challenges

The shortage of staff to monitor all the remote forest areas (Times of India, 2019,Times of India, 2021) makes the classification of encroachment based on types like buildings, roads, fields, and others challenging. There is also an absence of an openly available GIS map of forest encroachments in India, which could have been helpful for different anti-encroachment activities. Reducing human involvement in quantifying forest land encroachment may be a solution to get accurate figures. These issues may hamper timely eviction of encroachment to carry out afforestation in such reclaimed areas. The planting of species with fast growth and high CO_2 sequestrating ability in the location could have otherwise aided India's efforts to meet its forestry INDC goal of ensuring sequestration of 2.5-3 billion tonnes of CO_2 equivalent through additional afforestation by 2030.

1.6. Contours of a solution

Therefore, in reference to the paragraphs above, there is a need to quantify, classify, and geo-reference encroachment on forest land through automation. To achieve the above, remote sensing in the form of Very High Resolution(VHR) satellite imagery or drone imagery may be required. In India already satellite imagery has been used to assess the forest land area under encroachment in the north eastern state of Manipur (Sastry et al., 2007). However, this study (Sastry et al., 2007), cannot classify the encroachments in the form of the number of buildings or roads. It has given only the area under different types of encroachment. This issue is crucial because all the buildings, roads, agricultural fields within forest land may not be illegal. The suspected buildings, roads and others may be legally built or legalised through the diversion of forest land for non-forestry purposes (Government of India, 1980) or under the Forest Rights Act (Government of India, 2006) or regularised before the enactment of Forest Conservation Act 1980 (Government of India, 1980) or constructed by the State Forest Departments(SFDs) themselves. Therefore, only an assessment of built-up area or agricultural fields area (Sastry et al., 2007) may not be sufficient to distinguish the illegal from the legal.

A system that can rapidly identify any new encroachment on forest land is required to nip at the bud any such efforts. This system could be on the lines of Forest Survey of India's Fire Alert System (FAST) Version 3.0 ("FSI Fire Alert System (FAST) Version 3.0 ", 2019). Artificial intelligence methods in general and Computer vision in particular like image classification, image/semantic segmentation, and instance recognition may be necessary in this situation (Szegedy et al., 2016;Szeliski, 2011;Girshick et al., 2014;Haralick and Shapiro, 1985;L.-C. Chen et al., 2017).

This paper attempts to ascertain if the different types of forest encroachments happening in India can be automatically identified using existing artificial intelligence methods from VHR remote sensing imagery and distinguish the legal from the illegal.

Also, a method is proposed to develop a web GIS portal for viewing locations of encroachments and monitoring their eviction followed by afforestation.

2. Literature Review: AI Methods for Forest Encroachment Detection

2.1. AI for Building Detection in Remote Forest Areas

There are several means to extract buildings from satellite imagery using artificial intelligence techniques like image classification, semantic segmentation and instance segmentation (L.-C. Chen et al., 2017;Haralick and Shapiro, 1985). From only three-channel RGB satellite imagery, using a modified DeeplabV3+ module with a Dilated ResNet backbone, building footprints masks were generated with the incorporation of F-Beta objective by Jiwani et al in 2021 (Jiwani et al., 2021;Baheti et al., 2020). In 2021 Arndt et al identified that deep neural networks perform better in classifying urban buildings over different cities using diverse satellite imagery collections (Arndt and Lunga, 2021). QGIS an open-source RS/GIS software also has plugins for the identification of buildings and construction sites (GeoAlert, 2022). Using such tools initially may be useful since different state forest departments, and national agencies use ArcGIS/QGIS software.

2.2. AI for Road Network Identification on Forest Land

Road extraction from satellite imagery is necessary to identify illegally constructed roads in forest land. Such roads may be used by encroachers, timber smugglers, and wildlife poachers to expand their illegal activities. Artificial intelligence techniques are being used successfully by different researchers for road extraction.

Abdollahi et al found in 2020 that VNet+CEDL deep learning model was able to preserve boundary information and obtain high-resolution road segmentation maps from satellite imagery (Abdollahi et al., 2020). Rural roads detection from satellite imagery has been improved by an ensemble Wasserstein Generative Adversarial Network with Gradient Penalty (WGAN-GP) method called E-WGAN-GP by Yang et al in 2020 (Chuang Yang and Z. Wang, 2020), crucial for use in forest areas. Plugins capable of detection of roads are available with QGIS (GeoAlert, 2022).

2.3. AI for Agricultural Field Detection

Various researchers have applied different artificial intelligence techniques for the extraction of agricultural fields and identification of crops, a few are mentioned here.

Even with cloud cover, using deep learning, crop mapping was carried out from one shot hyperspectral satellite imagery by Meng et al in 2021 (Meng et al., 2021). Agricultural field boundaries in northern Germany were extracted by Wagner et al in 2020 from sensor independent RGB imagery using a combination of deep learning models and graph-based growing contours (GGC) method (Wagner and Oppelt, 2020). Crop type detection was carried out on RGB imagery from UAVs using Deep learning and transfer learning by Chew et al in 2020 in Rwanda (Chew et al., 2020). Paddy fields, which may constitute a large part of forest encroachments, were classified using deep learning from Dual Polarized Synthetic Aperture Radar (SAR) imagery by Chatterjee et al in 2020 (Chatterjee et al., 2021).

2.4. AI for Mine Detection

Illegal mining and tailings dams were detected in Brazil using deep neural networks and Sentinel-2 imagery processed in Google Earth Engine by Blaniuk et al (Balaniuk et al., 2020). They have brought to light 263 illegal mines using freely available low-cost data science tools (Balaniuk et al., 2020), which can be replicated in India also.

2.5. AI for Illegal Plantation and Tree Species Detection

There are several methods for tree species identification and tree crown detection, which may be used to identify illegal plantations in forest land. In 2020 Miyoshi et al were able to identify individual tree species in a dense forest area of semi-deciduous forest of the Brazilian Atlantic biome, from hyperspectral imagery using deep learning (Miyoshi et al., 2020). Individual Tree-Crown Detection and Species Classification were achieved by Pleşoianu et al using a Deep Learning Ensemble Model in 2020 (Pleşoianu et al., 2020).

2.6. AI for Deforestation Detection

Deforestation is a tell-tale sign of forest encroachment, and researchers worldwide are now using artificial intelligence for detecting and predicting it.Adarme et al in 2020 evaluated the effectiveness of four different deep learning models for automatic deforestation detection in Brazilian forests, finding Early Fusion (EF) and Siamese Network (SN) to be the most effective (Ortega Adarme et al., 2020). Deforestation probability assessment was carried out in Eastern India by Saha et al using multi-layer perceptron neural nets with hybrid ensemble classifiers in 2021 (Saha et al., 2021). In 2020 Irvin et al have classified the primary drivers of deforestation using a deep learning model called ForestNet in Indonesia, this may be of relevance for India also (Irvin et al., 2020).

3. India Case Study: Application Context and Challenges

3.1. Types of encroachments on forest land in India

The encroachment of forest land in India include construction of buildings, mining, agriculture, roads, illegal plantations, and all other land-related non-forestry activities within legal forest boundaries in contravention of different laws in India(Government of India, 1927, 1980, 2006; Kh et al., 2013). Illegal buildings in forest land have been reported from different states of India (Kerala High Court, 2021; National Green Tribunal, 2019).

The forests of the mineral-rich states of India have been affected by illegal mining (Kanchi Kohli, 2014; Ministry of Environment,Forests,Climate Change, 2021; Supreme Court of India, 2005). Encroachments are also in the form of illegal rubber plantations, cannabis and others (Ankur Paliwal, 2018; Times of India, 2020). Large scale deforestation is often a prelude to encroachment in Forests, therefore they also need to be monitored.

3.2. Current State of Forest Land Data in India

3.2.1. Availability of Geo-referenced Forest Land Data

In connection with the Lafarge Umiam Mining Pvt. Ltd. vs Govt of India W.P.(C) No.-000202-000202 / 1995, the Hon'ble Supreme Court of India issued guidelines for dealing with such future cases on 6th July 2011 (Kapadia, 2011). The guideline number (vii) at page 107 (Kapadia, 2011, p. 107) reads as follows -

> (vii) Creation and regular updating of a GIS based decision support database, tentatively containing inter-alia the district-wise details of the location and boundary of (i) each plot of land that may be defined as forest for the purpose of the Forest (Conservation) Act, 1980; (ii) the core, buffer and eco-sensitive zone of the protected areas constituted as per the provisions of the Wildlife (Protection) Act, 1972; (iii) the important migratory corridors for wildlife; and (iv) the forest land diverted for non-forest purpose in the past in the district. The Survey of India toposheets in digital format, the forest cover maps prepared by the Forest Survey of India in preparation of the successive State of Forest Reports and the conditions stipulated in the approvals accorded under the Forest (Conservation) Act, 1980 for each case of diversion of forest land in the district will also be part of the proposed decision support database.

As per this guideline of the Hon'ble Supreme Court of India, almost all states have completed or are in the process of completion of geo-referencing of forest land in their respective states. States like Odisha have even developed an Android mobile application called "KYFL @ ODISHA (Know Your Forest Location in Odisha)" (ORSAC, 2022a).

The guideline number (xii) (Kapadia, 2011, p. 110) also speaks of preparation of Geo-referenced district forest maps,as seen below-

> (xii) Completion of the exercise undertaken by each State/UT Govt. in compliance of this Court's order dated 12.12.1996 wherein inter-alia each State/UT Government was directed to constitute an Expert Committee to identify the areas which are "forests" irrespective of whether they are so notified, recognized or classified under any law, and irrespective of the land of such "forest" and the areas which were earlier "forests" but stand degraded, denuded and cleared, culminating in preparation of *Geo-referenced district forest-maps* containing the details of the location and boundary of each plot of land that may be defined as "forest" for the purpose of the Forest (Conservation) Act, 1980.

3.2.2. Geo-referenced Dataset of Legal Activities on Forest Land

Areas with buildings, roads, fields, rubber plantations and others within forest land that are legal and need to be excluded from encroachment identification exercise are-

1. Areas diverted for non-forestry purposes under the Forest (Conservation) Act 1980 Government of India, 1980. Till now 3,28,979 hectares of forest land have been diverted (Forest Survey of India, 2022b).
2. Buildings/roads/Forest Nurseries other structures built by the State Forest Department
3. Areas distributed under The Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 (Government of India, 2006). As of 30.11.2019 12.96 million acres or 5.24 million hectares of forest land has been distributed under this Act (Ministry of Tribal Affairs, 2020).
4. Areas given on lease for various purposes by the State Governments before the enactment of Forest (Conservation) Act 1980 (Government of India, 1980)

GIS polygons of diverted land (DL) as mentioned in sl no. 1 above, are available in the E-Green Watch portal of Forest Survey of India (Forest Survey of India, 2022a, 2022b). These may be merged to form a layer of diverted land for the entire country. This may also help ensure that construction/other activities are not taking place outside the approved area. Different State Forest Departments are having survey and GIS analysis units, which may be having the required spatial information as mentioned in sl no. 2 above. If not available, such spatial information can be easily prepared. Concerning areas as mentioned in sl no.3 above, states like Odisha and Tripura are carrying out GIS mapping using Android mobile apps (ORSAC, 2022b, 2022c).

Regarding land given under lease before the enactment of the Forest (Conservation) Act 1980 (Government of India, 1980), the leases if expired will have to be renewed as per the provisions of Forest (Conservation) Act 1980 (Government of India, 1980) which will provide GIS polygon data of such land in E-Green Watch portal (Forest Survey of India, 2022a, 2022b).

3.3. Implementation Challenges

3.3.1. Data Availability and Quality Challenges

Implementation of AI-based forest encroachment detection in India faces significant data availability and quality challenges that must be addressed for successful deployment. The absence of India-specific training datasets for various encroachment types represents a major obstacle, as most existing AI models are trained on Western architectural styles and landscapes that differ substantially from Indian contexts. Additionally, the high temporal variability of Indian landscapes due to pronounced seasonal changes (monsoon versus dry season) necessitates multi-seasonal imagery to avoid false positives. Cloud cover presents another persistent challenge, particularly in the northeastern states and Western Ghats where cloud-free days are limited, potentially creating significant gaps in monitoring continuity. Furthermore, the highly fragmented nature of both legal and illegal activities in Indian forests, with small-scale encroachments often measuring less than 0.1 hectares, demands very high resolution imagery that may be costly or difficult to acquire at national scales.

3.3.2. Technical Challenges

The technical implementation of an AI-based encroachment detection system encounters several formidable challenges related to both computational requirements and algorithmic limitations. The sheer scale of India's forest cover (approximately 77 million hectares) necessitates substantial computational infrastructure for processing high-resolution imagery at a national level, particularly when temporal analysis is required to detect new encroachments. Algorithm performance varies significantly across India's diverse biogeographic zones, with models trained in the relatively open deciduous forests of central India often performing poorly in the dense evergreen canopies of the Western Ghats or the complex mountainous terrain of the Himalayas. Technical expertise represents another limitation, as many state forest departments lack specialized personnel trained in advanced geospatial AI techniques, creating a knowledge gap between research capability and operational implementation. Furthermore, distinguishing between legal and illegal activities through automated means requires complex rule sets that can incorporate numerous exceptions and special cases that vary by region and legal framework, adding significant complexity to model development and validation protocols.

3.3.3. Administrative and Political Barriers

The implementation of an automated forest encroachment detection system in India confronts multifaceted administrative and political barriers that extend beyond technical considerations. Forest management in India operates under a complex jurisdictional framework where responsibilities are distributed across central, state, and local authorities, creating coordination challenges for implementing a unified monitoring system. Politically sensitive issues surrounding forest rights, particularly those related to indigenous communities under the Forest Rights Act of 2006, require careful handling to avoid potential conflicts when automated systems flag activities that may be legally contested or in regulatory gray areas. Additionally, cross-departmental coordination between Forest, Revenue, and Tribal Affairs departments—each maintaining separate and some-times contradictory land records—presents significant administrative hurdles for creating a consistent reference layer of legal activities. The system's implementation may also face resistance from vested interests benefiting from the current opacity in encroachment reporting, as increased transparency could threaten established patronage networks or expose previous administrative failures in preventing forest loss.

3.3.4. Resource and Cost Constraints

The development and implementation of a comprehensive AI-based forest encroachment detection system faces significant resource and cost constraints that must be realistically addressed for sustainable operation. Acquisition of very high resolution (VHR) satellite imagery presents a substantial recurring expense, with commercial providers charging approximately $10-25 per square kilometer, potentially amounting to millions of dollars annually for comprehensive national coverage of priority forest areas. Hardware infrastructure requirements for processing and storing massive imagery datasets represent another major cost center, necessitating either substantial capital investment in computing infrastructure or ongoing cloud computing expenses. Human resource costs for system development, operation, and field verification teams constitute a significant operational expense, requiring specialized personnel who command higher salaries than typical forestry staff. Additionally, the development of India-specific training datasets through professional annotation services represents a substantial initial investment, potentially costing $150,000-300,000 for comprehensive coverage of all encroachment types across India's diverse biogeographic zones, though this represents a one-time expense that could be partially offset through academic partnerships and crowdsourcing initiatives.

3.3.5. Need for Regular Updates and Maintenance

A forest encroachment detection system requires systematic regular updates and maintenance to remain effective, creating operational challenges beyond initial implementation. AI models require periodic retraining to address concept drift as encroachment patterns evolve over time, with encroachers potentially adapting their methods to avoid detection once they become aware of monitoring systems. The underlying base maps of forest boundaries and legal activities require constant updating as new land is legally diverted for non-forestry purposes, rights are granted under the Forest Rights Act, or forest boundaries are modified through legal processes. Technical infrastructure demands regular software updates, security patches, and hardware upgrades to maintain system performance and protect sensitive data from emerging cybersecurity threats. Additionally, the verification feedback loop must be continuously maintained through field staff training and engagement to ensure ground-truthing data continues flowing back into the system, preventing degradation of model accuracy over time. This continuous improvement cycle requires institutional commitment to long-term funding and staffing that transcends typical government project cycles, necessitating dedicated budget lines and performance metrics tied to system maintenance rather than just initial deployment.

4. Methodology: Framework for AI-based Encroachment Detection

4.1. Preparation of AOI for analysis

The area of interest(AOI) of remote sensing imagery where the encroachment identification processes (explained in 2.1) will be applied, has to be first determined.

$$AOI = L_{ForestLand} - L_{Legalactivities} \tag{1}$$

where:

AOI= Area of Interest to check for encroachment using artificial intelligence
$L_{\textbf{Forest Land}}$**=** GIS layer of forest land
$L_{\textbf{Legal activities}}$**=** GIS layer of the area to be excluded from checking for any encroachment identification exercise

The Forest Land layer comprises legally designated forests under the Indian Forest Act, 1927, including Reserved Forests, Protected Forests, and Unclassed Forests. Following the Supreme Court of India guidelines in the Lafarge Umiam Mining case (2011), most states have completed or are finalizing geo-referencing of their forest boundaries, with some states like Odisha developing mobile applications for public access to this information.

The Legal Activities layer must include four categories of authorized non-forest use: (1) areas diverted for non-forestry purposes under the Forest Conservation Act 1980 (approximately 328,979 hectares); (2) infrastructure built by State Forest Departments; (3) lands distributed under the Forest Rights Act 2006 (approximately 5.24 million hectares); and (4) pre-1980 leases granted by state governments. GIS data for these exemptions is available through the E-Green Watch portal, state Forest Department GIS units, and state-level FRA implementation tracking systems.

4.2. Data Requirements and Dataset Development

4.2.1. Preparation of India specific datasets and training of models

The success of any artificial intelligence project depends on the quality of datasets used for training the machine/deep learning model (H. Chen et al., 2020; Ding and Li, 2018). Therefore, to get accurate results we need to have India specific datasets for each encroachment type like buildings, road networks, agricultural fields, mines and plantations.

Currently, no comprehensive India-specific remote sensing datasets exist for these encroachment types. Existing repositories like Kaggle offer datasets for Western contexts (e.g., Massachusetts Roads and Buildings Datasets (Mnih, 2013)) but lack representation of Indian landscapes and settlement patterns. The development of India-specific datasets would provide significant benefits beyond encroachment detection, supporting broader geospatial AI applications throughout the country.

4.2.2. Data Collection Protocols and Standards

To ensure dataset quality and consistency, standardized protocols must be established regarding Imagery specifications, Annotation standards, Quality control process and Data augmentation. Data collection efforts should prioritize biogeographic representativeness, ensuring samples from all forest types in India (tropical, subtropical, montane, etc.) and capturing seasonal variations that significantly affect feature visibility and appearance.

4.3. Model Selection and Training Process

4.3.1. Criteria for Model Selection Based on Indian Conditions

Model selection must consider India's unique geographical and technical context like Performance across diverse landscapes, Resilience to seasonal variations, Computational efficiency and Adaptation to data limitations. Based on literature review, recommended model architectures include DeepLabV3+ with DenseNet backbone for building detection, MFPN (Multiple Feature Pyramid Network) for road detection, ResuNet-a for agricultural field boundaries, and enhanced Mask R-CNN for mining operations.

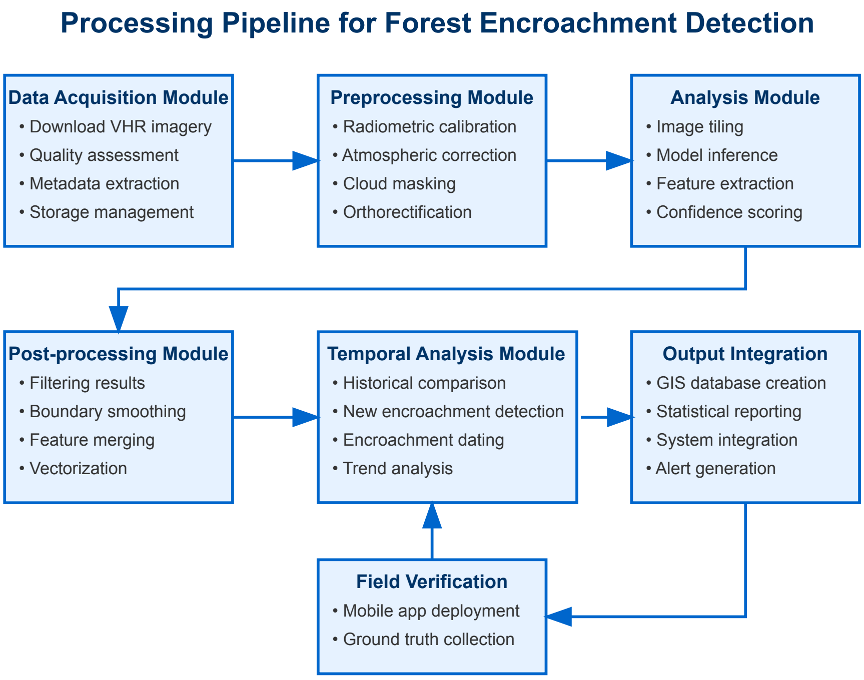
4.3.2. Training and Validation Protocols

A rigorous training and validation framework is essential for reliable model performance through Dataset partitioning, Hyperparameter optimization, Cross-validation strategy and Evaluation metrics. The testing and validation pipeline should explicitly include challenging scenarios (monsoon-affected imagery, partially obscured features, terrain shadows) to ensure robust real-world performance beyond ideal conditions.

4.4. Implementation Architecture

4.4.1. Processing Pipeline for VHR Satellite Imagery

Fig. 1 – Processing Pipeline



The operational implementation requires a structured processing pipeline(Fig. 1). The processing results will create geo-referenced databases of semantically segmented encroachment features that can be integrated with administrative boundaries to generate state-wise and district-wise statistics. This historical perspective is particularly valuable for legal proceedings and policy development, providing a chronological record of encroachment patterns.

4.4.2. Integration with Existing GIS Systems

The encroachment detection system must integrate seamlessly with existing government platforms like Forest Survey of India systems, State Forest Department GIS and National geospatial infrastructure. The integration architecture should employ standard OGC-compliant web services (WMS, WFS) for data sharing, with appropriate access controls to manage sensitive information while promoting transparency.

4.5. Validation and Verification Framework

4.5.1. Web GIS Platform Design

An interactive Web GIS platform (Fig(s). 2,4) will provide visualization and management capabilities. The platform design should follow the successful model of FSI's Forest Fire Portal, which has demonstrated effective integration of remote sensing alerts with field verification workflows at the national scale.

4.5.2. Ground Verification Protocol

Suspected encroachments identified by the AI system require field verification using mobile application and verification workflow. Once verification is complete, the web platform will enable tracking of both verification progress and subsequent enforcement actions, providing transparency for all stakeholders including policymakers, judiciary, and citizens.

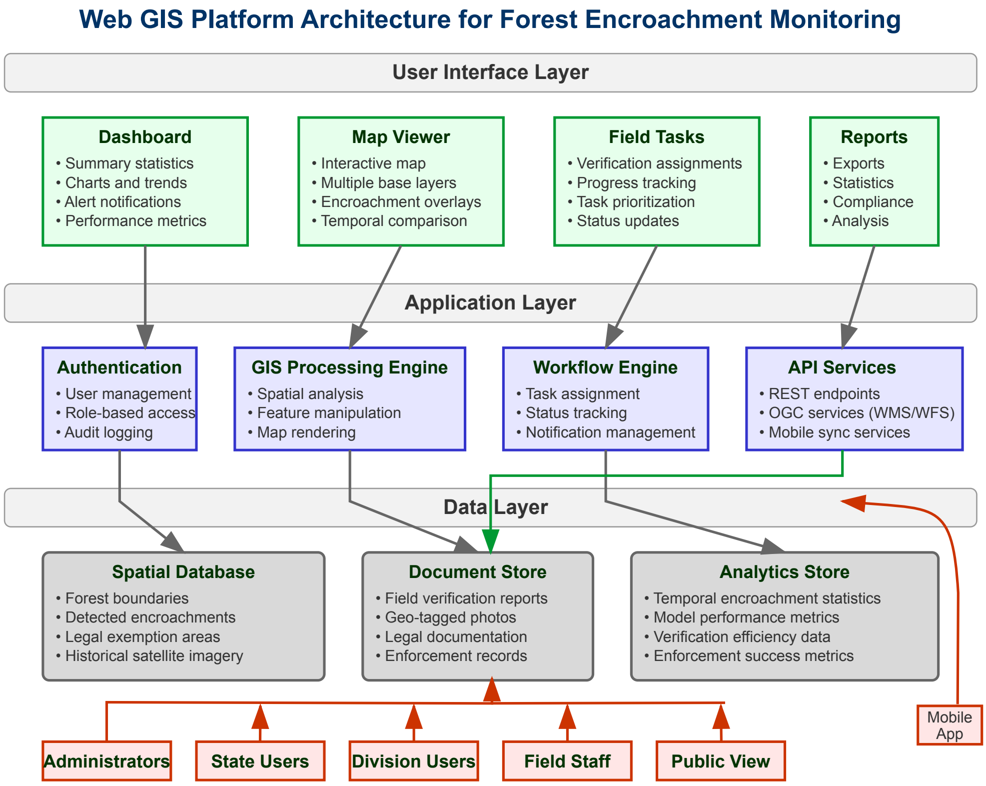


Fig. 2 – WebGIS Platform Architecture

4.5.3. Continuous Improvement through Feedback

The system design must incorporate feedback loop mechanisms for ongoing enhancement. This continuous improvement framework ensures the system evolves to address emerging encroachment patterns and adapts to regional variations in effectiveness, ultimately creating a learning system rather than a static monitoring tool.

5. Results and Discussion: Global Applications and Policy Implications

5.1. Lessons from India Applicable to Other Countries

The study of forest encroachment in Jiribam Sub-Division of Manipur (Kh et al., 2013) offers valuable insights applicable to similar challenges globally. As demonstrated in the Jiribam study, the application of remote sensing and GIS technologies allowed researchers to identify that 21.22% of the total area was under encroachment, primarily due to shifting cultivation practices (Kh et al., 2013).

In the Brazilian Amazon, where deforestation for agriculture is a significant concern, the Indian approach of combining high-resolution satellite imagery with ground verification could enhance existing monitoring systems by detecting smaller encroachments before they expand. Brazil's existing DETER system (Doblas et al., 2022) could be supplemented with AI-based detection to improve early intervention capabilities in remote areas.

5.2. Policy Implications for Forest Conservation

The findings from India's encroachment detection work suggest several important policy implications for forest conservation globally.

Integrated Jurisdictional Approaches: Forest monitoring technologies must be embedded within comprehensive jurisdictional frameworks that connect detection with enforcement and restoration. The Jiribam study

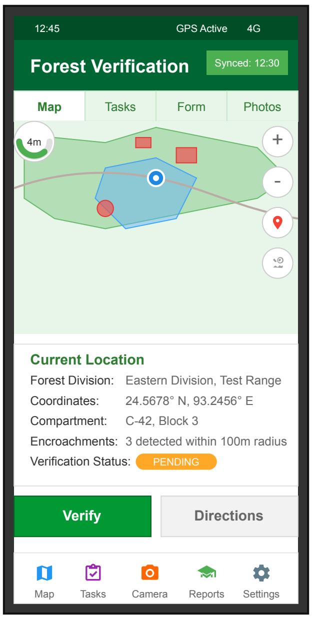


Fig. 3 – Field Verification Mobile Application Mock Up

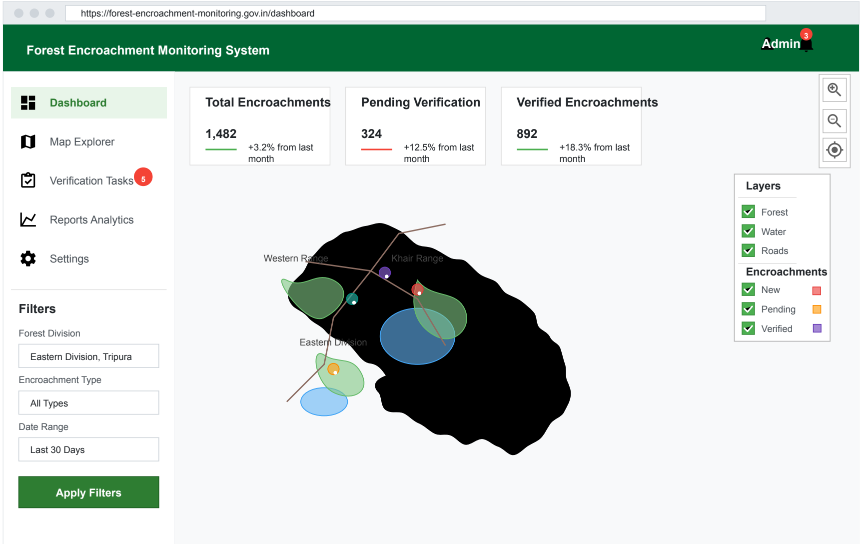


Fig. 4 – Desktop Web Application Mock Up

showed that merely identifying encroachment is insufficient; responding to it requires coordinated action across departments (Kh et al., 2013). Policy frameworks should establish clear protocols for inter-agency coordination when encroachment is detected.

Addressing Root Causes: The Jiribam study identified shifting cultivation as the primary driver of encroachment, with socio-economic factors like "food habits and misconceived food security feelings" contributing to continued forest clearance (Kh et al., 2013). Effective policies must address these root causes through alternative livelihood development and sustainable agriculture initiatives rather than focusing solely on enforcement.

Community Engagement: The recommendation from the Jiribam study to "manage jhum affected areas...without neglecting the demands and needs of the farmers" (Kh et al., 2013) emphasizes the importance of community-based conservation approaches. Policies should recognize indigenous and traditional forest rights while providing pathways to more sustainable practices through collaborative management. Technology Access and Standardization: For monitoring systems to be effective globally, policies need to support technology transfer, capacity building, and data standardization. The methodologies used in India can be adapted to different contexts, but require policy frameworks that enable access to satellite imagery, analysis software, and training for local forestry officials.

5.3. Integration with Climate Change Mitigation Efforts

AI-based encroachment detection systems directly support global climate change mitigation efforts, particularly within frameworks like REDD+ (Reducing Emissions from Deforestation and Forest Degradation) (Duchelle et al., 2018). This can be achieved through Enhanced Carbon Accounting, Supporting Results-Based Payments, Addressing Forest Degradation and Protecting Ecosystem Services.

5.4. Recommendations for Implementation in Various Contexts

Based on the Indian experience and the Jiribam study in particular, implementation recommendations can be tailored to different contexts:

For National Governments:

1. Establish comprehensive legal frameworks that clearly define forest boundaries
2. Develop institutional coordination mechanisms between rstakeholders
3. Invest in capacity building for technical staff at multiple levels of government
4. Create transparent monitoring dashboards that promote accountability and public engagement

For Conservation Organizations:

1. Support development of regionally-specific training datasets for AI algorithms
2. Facilitate technology transfer and capacity building between countries facing similar challenges
3. Develop community-based monitoring protocols that complement satellite detection
4. Advocate for funding mechanisms that support sustained monitoring rather than short-term projects

For Development Partners:

1. Fund pilot implementations that demonstrate effectiveness in different contexts
2. Support creation of regional centers of excellence for technology adaptation
3. Integrate encroachment monitoring with broader sustainable development initiatives
4. Invest in alternative livelihoods for forest-dependent communities

6. Conclusion

This paper demonstrates that current artificial intelligence techniques provide a viable foundation for automating forest encroachment detection in India. The comprehensive framework proposed here—integrating deep learning models with GIS systems, field verification protocols, and administrative workflows—addresses a critical need in forest conservation governance. By enabling systematic monitoring of encroachments through building detection, road network identification, and land use classification, this approach could substantially increase available land for afforestation efforts. The implementation challenges identified—including data availability, computational requirements, and administrative coordination—while significant, can be addressed through phased deployment, starting with high-priority forest regions.

Beyond theoretical potential, next steps should include pilot implementations across diverse biogeographic zones, development of India-specific training datasets, and quantitative evaluation of model performance under varying seasonal conditions. The long-term success of such a system depends not merely on technical implementation, but on integration with existing governance structures and community engagement initiatives. If successfully deployed, this approach could serve as a model for other forest-rich nations facing similar challenges, ultimately contributing to global climate change mitigation efforts by protecting the carbon sequestration potential of forest ecosystems. The return on investment—both environmental and economic—justifies the resources required for implementation, particularly as India strives to meet its commitment of creating an additional carbon sink of 2.5-3 billion tonnes of CO_2 equivalent by 2030.

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Use of AI

During the preparation of this work, the author(s) used Claude 3.7 Sonnet in order to check grammar, and correct LaTeX code formatting. After using this tool/service, the author(s) reviewed, edited, made the content their own and validated the outcome as needed, and take(s) full responsibility for the content of the publication.

Conflict Of Interest (COI)

There is no conflict of interest.

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