

AI-Driven Wildfire Risk Prediction and Intelligent Fire-Fighting Systems

Balabhaskar Kalparapu¹, Matta Harshita², Bandla Nayana Lakshmi Pranava³,
Ala Vinuthna⁴, Bolla Amrutha⁵

¹*Dept. of AI&DS, KL University Vaddeswaram, India*

^{2,4,5}*Dept. of CSE, KL University Vaddeswaram, India*

³*Dept. of CS&IT, KL University Vaddeswaram, India*

Abstract— Wildfires represent an escalating global crisis, threatening ecosystems, human settlements, and economic stability with unprecedented intensity. The convergence of climate change, land-use transformation, and increasing human encroachment into wildland-urban interfaces has amplified both the frequency and severity of fire disasters worldwide. This research presents a comprehensive artificial intelligence framework that seamlessly integrates predictive risk assessment with intelligent fire-fighting operations, establishing a closed-loop system for proactive wildfire management. The methodology leverages ISRO's BHUVAN geospatial platform India's national geo-portal developed by the Indian Space Research Organisation which provides multi-sensor, multi-platform, and multi-temporal satellite imagery along with critical disaster management services including forest fire SMS alerts, spatial fire information, drought indicators, and land use/land cover data at multiple scales. By integrating BHUVAN-derived datasets with meteorological observations and historical fire records within an ensemble machine learning architecture, the proposed model achieves 89.2% accuracy in predicting high-risk zones across Andhra Pradesh. Beyond risk prediction, the framework incorporates advanced fire-fighting algorithms: a dynamic resource dispatch system optimizing suppression resource allocation, a multi-agent reinforcement learning framework coordinating autonomous aerial suppression units, a genetic algorithm for strategic firebreak placement, and a convolutional neural network achieving 94.3% accuracy for real-time fire detection from aerial imagery. The integrated system demonstrates a 35% improvement in containment efficiency and 42% reduction in potential fire spread compared to conventional approaches. This unified framework represents a paradigm shift from reactive fire suppression to intelligent, data-driven wildfire management, providing a scalable model for implementation in fire-prone regions globally.

Index Terms— Wildfire Prediction, Artificial Intelligence, Machine Learning, BHUVAN, ISRO, Remote Sensing, Geospatial Analysis, Fire-Fighting Algorithms, Reinforcement Learning, Ensemble Methods, Disaster Management

I. INTRODUCTION

A. The Global Wildfire Crisis

Wildfires have emerged as one of the most formidable environmental challenges of the twenty-first century, exacting devastating tolls on natural ecosystems, human communities, and economic infrastructure across all inhabited continents. The past decade has witnessed an alarming escalation in fire activity, with record-breaking events occurring in Australia, California, the Mediterranean basin, the Amazon rainforest, and Siberia. These catastrophic fires have collectively consumed millions of hectares of forest, destroyed thousands of structures, claimed hundreds of lives, and generated carbon emissions equivalent to entire nations' annual outputs.

The intensification of wildfire regimes stems from a complex interplay of factors. Climate change has fundamentally altered fire weather conditions, extending fire seasons, increasing the frequency of extreme fire weather days, and amplifying drought severity across vast regions. Land-use changes, including agricultural expansion, forest fragmentation, and the proliferation of wildland-urban interfaces, have introduced new ignition sources and transformed landscapes into highly flammable fuel complexes. Compounding these challenges, decades of fire suppression policies have allowed unprecedented fuel accumulation in many ecosystems, creating conditions where fires ignite more readily and

spread with extraordinary intensity.

India exemplifies these global trends in acute form. According to the National Remote Sensing Centre, over 36 percent of forest areas in India experience fire events annually, with the frequency and extent of fires showing upward trajectories. The state of Andhra Pradesh, situated in southeastern India, represents a particularly vulnerable region characterized by semi-arid climatic conditions, extensive dryland ecosystems, and pronounced seasonal drought patterns. The Rayalaseema belt encompassing Anantapur, Kurnool, and Chittoor districts experiences persistent water deficits, summer temperatures frequently exceeding 40 degrees Celsius, and extensive agricultural burning practices, creating conditions highly conducive to fire ignition and rapid spread.

B. ISRO BHUVAN: India's Geospatial Foundation

The Indian Space Research Organisation (ISRO) has established BHUVAN as the national geo-portal, serving as a comprehensive repository of Earth observation data, services, and analytical tools [5]. BHUVAN (meaning "Earth" in Sanskrit) showcases India's Earth observation capabilities from the Indian Remote Sensing (IRS) series of satellites, providing multi-sensor, multi-platform, and multi-temporal satellite imagery that can be visualized in both 2D and 3D environments [6].

The platform's significance for disaster management cannot be overstated. BHUVAN integrates thematic information interpreted from satellite imagery as vector layers alongside near real-time information from Automatic Weather Stations (AWS) and disaster support services [7]. Within the Disaster Management Support Programme of ISRO, BHUVAN provides critical services including forest fire SMS alerts, spatial fire information, periodic agricultural drought assessment, and various thematic applications [8]. These services are disseminated through the Decision Support Centre at the National Remote Sensing Centre (NRSC), serving as ISRO's single window for disaster management information.

The thematic datasets available through BHUVAN encompass a comprehensive suite of environmental variables essential for fire risk assessment. Land use and land cover data are available at multiple scales: 1:250,000 scale for regional planning and research, 1:50,000 scale for development and research studies

across three cycles (2005-06, 2011-12, and 2015-16), and 1:10,000 scale district-level data under the SISDP program [5]. Land degradation data at 1:50,000 scale provides critical insights into vegetation stress and fuel condition. Vegetation indices including NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index) enable quantification of vegetation health and moisture content. Soil moisture indicators including SMI (Soil Moisture Index) and SASI (Soil Adjusted Spectral Index) provide direct measurements of fuel moisture conditions.

C. Limitations of Traditional Fire Management

Conventional fire management systems have historically operated within a reactive paradigm, mobilizing suppression resources only after fires have ignited and begun spreading. This approach suffers from fundamental limitations that compromise its effectiveness in addressing contemporary wildfire challenges. Manual detection through observation posts and community reporting introduces substantial delays during which small ignitions can escalate into large, uncontrollable fires. Satellite-based active fire detection systems, while valuable for situational awareness, provide information only after fires are already burning, precluding preventive intervention. Traditional risk assessment methodologies typically employ simplistic indices that fail to capture the complex, non-linear interactions among environmental variables that determine fire susceptibility. The absence of integrated, predictive frameworks means that resource allocation for fire prevention remains largely static and reactive rather than dynamically optimized based on anticipated risk levels. Furthermore, firefighting operations rely heavily on manual decision-making and historical experience, often resulting in suboptimal resource deployment, inefficient suppression strategies, and compromised responder safety.

D. Research Contributions

This research presents an integrated artificial intelligence framework that bridges predictive risk assessment and intelligent fire-fighting operations. The specific contributions include:

- 1) Development of an ensemble machine learning model integrating ISRO BHUVAN geospatial data with meteorological observations, achieving

89.2% accuracy in predicting high-risk zones across Andhra Pradesh.

- 2) Implementation of advanced fire-fighting algorithms including dynamic resource dispatch, multi-agent reinforcement learning for aerial suppression, genetic algorithm-based firebreak placement, and CNN-based real-time fire detection.
- 3) Integration of diverse wildfire-specific datasets from global sources alongside BHUVAN's thematic datasets to ensure model generalizability.
- 4) Demonstration of operational improvements: 35% enhancement in containment efficiency and 42% reduction in potential fire spread.
- 5) Establishment of a scalable framework applicable to fire-prone regions globally, with validation in Andhra Pradesh.

II. LITERATURE REVIEW

A. Remote Sensing and Fire Monitoring

The application of remote sensing technology to fire monitoring has evolved through distinct generations of advancement. Early efforts focused on active fire detection using thermal infrared bands, with the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument providing systematic global observations since 2000. The MODIS active fire product has enabled researchers to compile extensive fire databases spanning multiple decades, establishing the foundation for subsequent predictive modeling [3]. More recent sensors, including VIIRS (Visible Infrared Imaging Radiometer Suite), offer enhanced spatial resolution and nighttime detection capabilities, capturing fires previously missed by coarser-resolution instruments.

Beyond active fire detection, satellite data have enabled characterization of vegetation conditions that influence fire susceptibility. The Normalized Difference Vegetation Index, derived from red and near-infrared reflectance measurements, provides quantitative information about vegetation health, density, and moisture content [1]. Areas exhibiting low NDVI values typically indicate stressed or sparse vegetation more susceptible to ignition and rapid fire spread. Land surface temperature data derived from thermal infrared measurements offer insights into thermal conditions influencing fuel flammability, with higher temperatures accelerating fuel drying and

reducing moisture content.

ISRO's BHUVAN platform represents a significant advancement in India's remote sensing capabilities, providing systematic access to IRS satellite data products and thematic services [5]. The platform's forest fire monitoring services, integrated with the Disaster Management Support Programme, deliver near real-time alerts and spatial information that form the foundation for predictive modeling [9].

B. Machine Learning for Fire Risk Assessment

Machine learning techniques have demonstrated substantial promise for fire risk assessment, consistently outperforming traditional statistical approaches. Researchers have explored diverse algorithms for predicting fire occurrence, susceptibility, and potential spread patterns. Deep learning approaches, particularly convolutional neural networks, have proven effective for identifying fire-prone vegetation zones by learning spatial patterns associated with historical fire events from satellite imagery [2].

Ensemble methods have emerged as particularly powerful for fire risk modeling. Random Forest, which constructs ensembles of decision trees trained on bootstrap samples, offers exceptional performance due to its ability to handle high-dimensional data, capture non-linear relationships, and provide interpretable measures of variable importance [10]. The algorithm's resistance to overfitting makes it especially suitable for environmental applications where data quality may vary across sources.

Gradient Boosting approaches, which sequentially build ensembles with each new model correcting errors made by previous models, have also demonstrated strong performance. XGBoost and Light GBM implementations offer computational efficiency and regularization capabilities that further enhance predictive accuracy [4]. Comparative studies consistently show ensemble tree-based methods outperforming support vector machines and neural networks for tabular environmental data.

C. BHUVAN Datasets for Wildfire Research

ISRO's BHUVAN platform provides comprehensive datasets essential for wildfire research in the Indian context:

Thematic Datasets: BHUVAN offers land use and land cover data at multiple scales (1:250,000, 1:50,000, and

1:10,000 scales), enabling characterization of fuel types and landscape patterns that influence fire behavior [5]. Land degradation data at 1:50,000 scale provides insights into vegetation stress conditions that increase fire susceptibility.

Vegetation and Drought Indicators: The platform integrates multiple vegetation indices including NDVI and NDWI for quantifying vegetation health and moisture content [7]. Soil moisture indicators including SMI and SASI provide direct measurements of fuel moisture conditions critical to ignition potential.

Forest Fire Services: BHUVAN's disaster management support system provides forest fire SMS alerts, spatial and textual fire information, and visualization tools for fire-affected regions [8]. These services are delivered through the Decision Support Centre at NRSC.

State-Level Collaborations: BHUVAN's partnerships with state forest departments provide validated ground truth data. The Karnataka Forest Department collaboration enables visualization of forest fires, assets, changes in forest cover, villages, water bodies, landscapes, national parks, and beat boundaries [9]. The Himachal Pradesh Forest Department partnership provides administrative level data and fire alert SMS systems for officials [9].

D. Fire-Fighting Algorithms and Operational Systems
Research on fire-fighting algorithms has advanced substantially, with increasing emphasis on optimization and autonomy. Resource allocation algorithms for wildfire suppression have evolved from simple heuristics to sophisticated optimization frameworks. Dynamic programming approaches have been applied to dispatching suppression resources, though computational complexity has limited their application to small-scale problems.

Reinforcement learning has emerged as a promising approach for tactical fire suppression. Multi-agent reinforcement learning frameworks enable coordination among multiple suppression resources, with agents learning optimal strategies through interaction with simulated environments [11]. These approaches have demonstrated significant improvements in containment efficiency compared to traditional dispatch protocols.

Convolutional neural networks have achieved remarkable performance for fire detection from aerial imagery, with architectures like YOLOv8 achieving

detection accuracies exceeding 90% with inference times suitable for real-time operation. The FLAME (Fire Luminosity Airborne-based Machine Learning Evaluation) dataset has enabled systematic training and evaluation of detection algorithms across varied conditions.

III. METHODOLOGY

A. Study Area

The study area encompasses the state of Andhra Pradesh, located in southeastern India between latitudes 12°41' and 19°07' North and longitudes 76°46' and 84°46' East. The state spans approximately 162,975 square kilometers and exhibits diverse geographic features including coastal plains along the Bay of Bengal, the Eastern Ghats mountain range, and the interior drylands of the Rayalaseema region.

BHUVAN provides high-resolution datasets up to 2.5 meters for Andhra Pradesh, enabling detailed spatial analysis at village and sub-village scales [8]. The state's inclusion in BHUVAN's high-resolution coverage ensures availability

B. Data Collection and Integration

1) **BHUVAN Primary Data Sources:** The predictive model was developed using data from ISRO's BHUVAN geospatial platform:

- **Thematic Datasets:** Land use and land cover data at 1:50,000 scale for the 2015-16 cycle, land degradation data at the same scale [5].
- **Vegetation Indices:** NDVI and NDWI products derived from Resourcesat satellite data, monthly composites at 25-meter resolution [7].
- **Drought Indicators:** Agricultural drought products including NDVI anomaly, NDWI anomaly, SMI, and SASI from BHUVAN's disaster management services [8].
- **Forest Fire Alerts:** Historical Forest fire SMS alert data and spatial fire information covering 2010-2024 [9].
- **High-Resolution Imagery:** Cartosat-1 (2.5m) merged with Resourcesat-1 (5.8m) high-resolution imagery for Andhra Pradesh [8].

2) **Supplementary Data Sources:** Additional data sources integrated include meteorological data from ECMWF ERA5 reanalysis, global fire datasets (Algerian Forest Fires, IberFire, Western United States Ignition), and ground truth records

from the Andhra Pradesh Forest Department

C. Feature Engineering

Key features extracted from BHUVAN data include:

- Vegetation Health Features: NDVI and NDWI values with temporal trends
- Drought Severity Features: SMI, SASI, and integrated Drought Index
- Thermal Features: Land surface temperature (daytime and nighttime)
- Fuel Characterization: Land use/land cover classifications
- Topographic Features: Elevation, slope, aspect from Car- tosat DEM
- Historical Fire Features: Fire frequency and intensity from BHUVAN alerts

All features were normalized using Min-Max scaling to ensure uniform contribution during model training

D. Model Development

The Random Forest algorithm was selected as the primary modeling approach, with Gradient Boosting and Support Vector Machines implemented for comparison. The dataset was partitioned into 80% training and 20% testing subsets using stratified sampling.

Performance was evaluated using accuracy, precision, recall, and F1-score metrics.

E. Advanced Fire-Fighting Algorithms

- 1) Dynamic Resource Dispatch Algorithm: The Dynamic Resource Dispatch (DRD) algorithm optimizes real-time deployment of fire-fighting resources

$$\min_{x_{ij}} \sum_{i=1}^n \sum_{j=1}^m (C_{ij}x_{ij} + D_i \cdot (1 - e^{-\lambda \sum_j x_{ij}}))$$

- 2) Multi-Agent Reinforcement Learning: A multi-agent reinforcement learning framework coordinates autonomous fire-fighting units

$$Q(s, a) = r(s, a) + \gamma \max_{a'} Q(s', a')$$

- 3) Convolutional Neural Network for Fire Detection: A YOLOv8-based architecture achieved:

- Fire detection accuracy: 94.3%
- Smoke detection accuracy: 91.7%
- False positive rate: 3.2%
- Inference time: 45 ms per frame

- 4) Genetic Algorithm for Firebreak Placement: Fitness function for firebreak optimization

$$Cost = \frac{\sum_{i=1}^n V_i \cdot (1 - e^{-\lambda d_i})}{(\text{breaks}) + \text{Length}(\text{breaks})}$$

Table I Algorithm Performance Metrics

Algorithm	Improvement	Response Time	Resource
Dynamic Resource Dispatch	+35% containment	-42%	+28%
Multi-Agent RL	+23% efficiency	-38%	+31%
CNN Fire Detection	94.3% accuracy	45 ms	N/A
Genetic Firebreak	42% spread reduction	N/A	-28% c

IV. RESULTS AND ANALYSIS

A. Model Performance Evaluation

The Random Forest model achieved an accuracy of 89.2 percent in predicting fire risk zones. Precision was 87.5 percent, recall 90.3 percent, and F1-score 88.9 percent.

Table II Performance Comparison of Machine Learning Models

Model	Accuracy	Precision	Recall	F1-Score
Random Forest	89.2%	87.5%	90.3%	88.9%
Gradient Boosting	85.7%	84.2%	86.5%	85.3%
Support Vector Machine	81.5%	79.8%	82.1%	80.9%

B. Variable Importance Analysis

BHUVAN-derived features contributed significantly to predictive accuracy:

- Vegetation Health (NDVI/NDWI): 24.0%
- Land Surface Temperature: 22.0%
- Drought Indicators (SMI/SASI/DI): 20.0%
- Land Use/Land Cover: 16.0%
- Historical Fire Frequency: 12.0%
- Topography: 6.0%

C. Spatial Patterns of Fire Risk

The Rayalaseema belt (Anantapur, Kurnool, Chittoor districts) recorded the highest predicted risk scores. Coastal districts exhibited lower risk, while the Eastern Ghats region displayed intermediate scores with substantial spatial variability.

D. Model Validation

High-risk zones identified by the model accounted for 78 percent of all fire incidents during the validation period, despite covering only 24 percent of the state's geographic area.

V. DISCUSSION

The strong performance of the Random Forest model demonstrates the feasibility of AI-driven approaches for proactive fire disaster management. BHUVAN-derived features vegetation health indicators, land surface temperature, and drought metrics emerged as the dominant predictors, validating ISRO's investment in Earth observation products for disaster management.

The concentration of predicted high-risk areas in the Rayalaseema belt aligns with observed fire patterns and high-light regions requiring priority attention. BHUVAN's high-resolution imagery for Andhra Pradesh enables detailed analysis of fuel conditions contributing to this elevated risk.

Comparison with previous research shows the achieved accuracy of 89.2% exceeds typical ranges of 75-85% reported in prior studies. This improved performance reflects comprehensive integration of BHUVAN's multi-source datasets.

VI. CONCLUSION AND FUTURE WORK

A. Summary

This research demonstrated the effectiveness of integrating ISRO's BHUVAN geospatial data with artificial intelligence for wildfire risk prediction, achieving 89.2% accuracy for fire risk prediction in Andhra Pradesh. The framework integrates advanced fire-fighting algorithms achieving 35% improvement in containment efficiency and 42% reduction in potential fire spread.

B. Future Directions

Future work includes integration of additional BHUVAN products, development of real-time prediction systems, extension to other environmental hazards, and deployment of customized mobile applications for forest officials across India.

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