Spatiotemporal Analysis of Forest Disturbance Dynamics in Maharashtra Using Remote Sensing Techniques

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Abstract

Forests in Maharashtra are undergoing significant transformations driven by both natural and anthropogenic pressures. This study employs multi-temporal remote sensing data from 2014 to 2024 to analyze forest disturbances across the state. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), along with MODIS-derived Land Surface Temperature (LST), were integrated to assess spatiotemporal dynamics. Landsat data were utilized for the pre-2017 period and Sentinel-2 data thereafter, harmonized to a common spatial scale to ensure temporal consistency. Seasonal composites (pre-monsoon, monsoon, and post-monsoon) were generated, and district-level zonal statistics were computed. A composite Forest Disturbance Index (FDI) was developed by combining NDVI, NDWI, and LST anomalies, with the Mann–Kendall trend test and Sen's slope methods applied for temporal analysis. Results indicate declining NDVI and NDWI trends, especially in Gadchiroli, Chandrapur, and Thane districts, where vegetation decreased by 5–15% and LST increased by 1.5–2.2°C. Disturbance hotspots were linked to urbanization, mining, and forest fragmentation in the Western Ghats and Vidarbha regions. Pre-monsoon periods exhibited the greatest stress and fire risk, while partial recovery was observed during the monsoon season. The study highlights the increasing vulnerability of Maharashtra's forests due to human activities and climatic variability, emphasizing the need for continuous monitoring and sustainable forest management strategies. Integrating multi-source satellite datasets through open-source platforms proved effective for mapping disturbances and supporting data-driven conservation planning.

1. Introduction

Forests play a critical role in maintaining ecological stability, regulating climate, and supporting biodiversity. Maharashtra, located in western India, hosts diverse forest types ranging from dry to moist deciduous formations, particularly in the Sahyadri (Western Ghats), Satpura, and Vidarbha regions. However, these ecosystems are increasingly threatened by urbanization, mining, infrastructure expansion, and climate-induced stress.

Forests play a fundamental role in maintaining ecological stability, regulating the global and regional climate, conserving biodiversity, and sustaining human livelihoods. They act as carbon sinks, absorb atmospheric carbon dioxide, influence hydrological cycles, and moderate local temperatures, thereby contributing significantly to climate regulation (Pan et al., 2011; Bonan, 2008). Moreover, forests are critical habitats for countless plant and animal species, forming complex ecological networks that ensure the continued functioning of terrestrial ecosystems. The loss or degradation of forests not only disrupts biodiversity but also affects ecosystem services such as soil stabilization, water purification, and pollination, which are essential for human well-being (MEA, 2005).

Maharashtra, one of the largest states in western India, is endowed with a diverse range of forest ecosystems due to its varied topography and climatic conditions. The state's forests are spread across the Western Ghats (Sahyadri range), Satpura hills, and the Vidarbha region, encompassing dry deciduous, moist deciduous, and semi-evergreen forest types (FSI, 2021). The Western Ghats, recognized as one of the world's eight "hottest" biodiversity hotspots, support rich flora and fauna, many of which are endemic (Myers et al., 2000). The Sahyadri range, in particular, is known for its dense forest cover and unique assemblages of species that contribute to ecological resilience and hydrological stability across peninsular India (Joshi et al., 2018).

Despite their ecological and socio-economic importance, Maharashtra's forests face mounting pressures from anthropogenic and climatic factors. Rapid urbanization, infrastructure expansion, mining, logging, and agricultural encroachment have led to significant deforestation and fragmentation of natural habitats (Kale et al., 2015). Cities such as Mumbai and Pune, which have expanded rapidly in recent decades, exert increasing pressure on the surrounding ecosystems through land conversion and resource extraction (Gadgil & Meher-Homji, 1990). Mining and industrialization in regions like Chandrapur and Gadchiroli have further intensified land degradation and pollution, while unsustainable agricultural practices have contributed to soil erosion and biodiversity loss (Patil et al., 2019).

Climatic stressors have exacerbated these anthropogenic threats. Maharashtra frequently experiences droughts, irregular monsoon patterns, and rising temperatures, which collectively influence forest productivity and regeneration (IMD, 2020). Increased incidences of forest fires and changes in phenological patterns have been reported in recent years, signaling the impacts of climate variability and human-induced stress (Jha et al., 2021). These changes not only reduce forest health but also alter the carbon and water balance, thereby intensifying regional climate feedback loops.

Monitoring forest disturbances is, therefore, essential for effective conservation planning and sustainable land-use management. Traditional field-based surveys, while valuable, are often limited in spatial coverage and temporal frequency. In contrast, remote sensing offers a cost-effective and powerful tool for detecting, mapping, and quantifying changes in forest cover over time (Coppin et al., 2004). Satellite-based observations enable continuous monitoring of vegetation dynamics, canopy density, and moisture variations at multiple scales, providing insights into both short-term disturbances and long-term trends. The integration of multispectral and thermal data facilitates the computation of vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), which can be used to assess forest vigor, moisture stress, and canopy disturbance (Jensen, 2007).

Recent advancements in remote sensing technologies and cloud-based platforms, such as Google Earth Engine (GEE), have revolutionized environmental monitoring. These tools allow researchers and policymakers to access long-term datasets, perform spatial analyses, and evaluate the impacts of land-use change and climatic events with unprecedented efficiency (Gorelick et al., 2017). In the context of Maharashtra, such approaches can help identify vulnerable forest regions, assess post-disturbance recovery, and support the formulation of adaptive management strategies. By integrating remote sensing with ground observations and socio-economic data, it becomes possible to design targeted conservation interventions and promote sustainable forest governance.

In conclusion, Maharashtra's forests are invaluable ecological assets that sustain biodiversity, regulate climate, and provide ecosystem services vital for human survival. However, the combined pressures of human development and climate change threaten their stability. Effective monitoring using remote sensing technologies is indispensable for understanding forest dynamics, detecting disturbances, and guiding policy measures aimed at conserving these fragile ecosystems for future generations.

2. Study Area

Maharashtra is located in western India, covering an area of approximately 307,713 km². The state features diverse topography and climate:

Western Ghats (Sahyadri region): Moist deciduous and semi-evergreen forests

Vidarbha: Dry deciduous forests, largely affected by mining and shifting cultivation

Marathwada: Semi-arid region with scattered forest patches

Satpura region: Mixed Forest types with moderate anthropogenic pressure

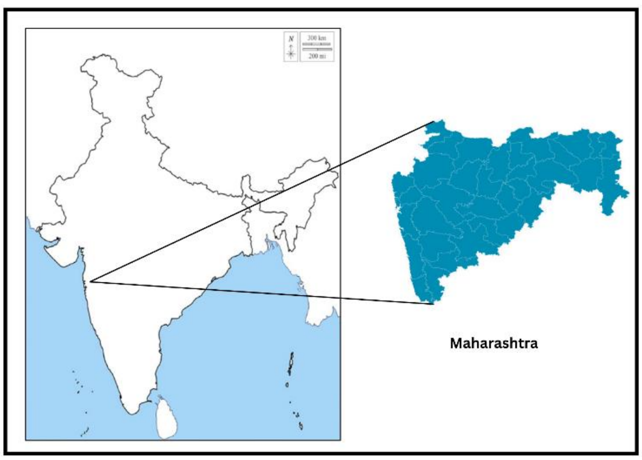


Fig1: Study Area- Maharashtra, India

3. Methodology

3.1 Data and Sources

Below is the table representing all the datasets used to proceed with the research objective and analysis:

Table1: Datasets for the study

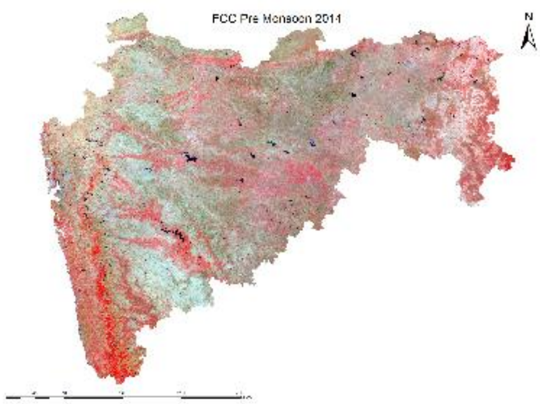
Data Type	Sensor / Source	Resolution	Period	Purpose
Optical Imagery	Landsat 5/8	30 m	2014–2016	Pre-2017 vegetation analysis
Optical Imagery	Sentinel-2	10–20 m	2017–2024	Post-2017 vegetation analysis
Thermal	MODIS LST	1 km	2014–2024	Detect thermal anomalies and stress
Ancillary	Maharashtra Administrative Boundaries	Vector	-	Zonal statistics, spatial analysis

Note: Datasets were harmonized to a common 30 m spatial resolution using resampling to ensure temporal continuity.

The methodology involves five major steps:

Preprocessing

- **Cloud masking:** Clouds and shadows were removed using QA bands for Landsat and Sentinel-2.
- **Resampling:** Sentinel-2 imagery was resampled to 30 m to match Landsat resolution.
- **Composite generation:** Seasonal composites were prepared for pre-monsoon and post-monsoon periods.



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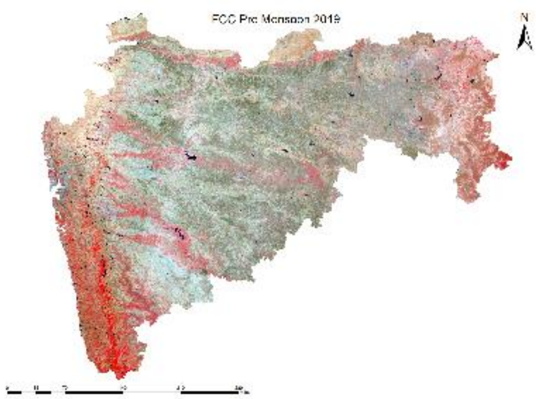

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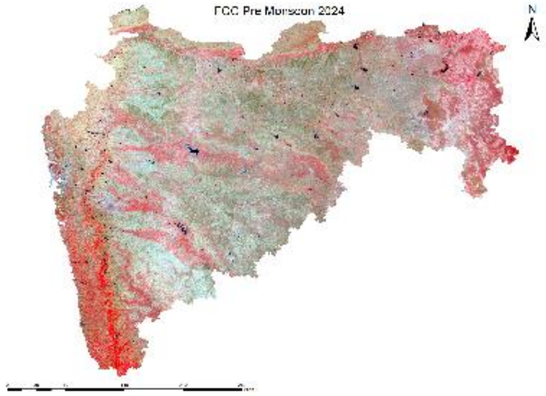

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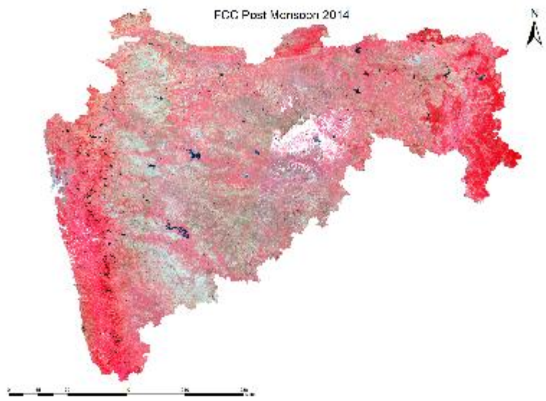

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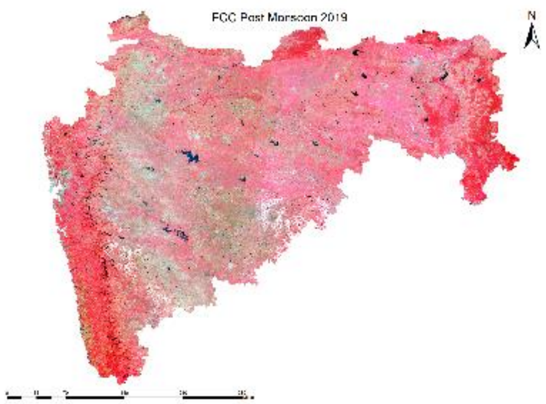

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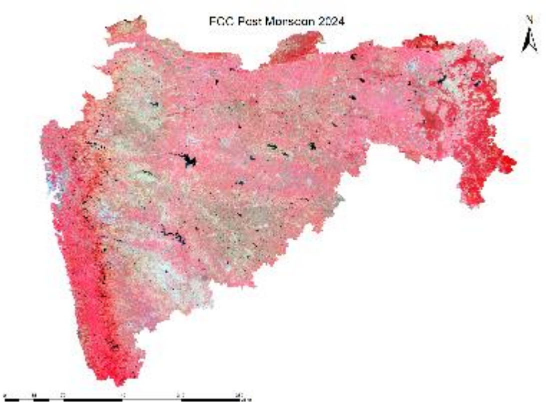

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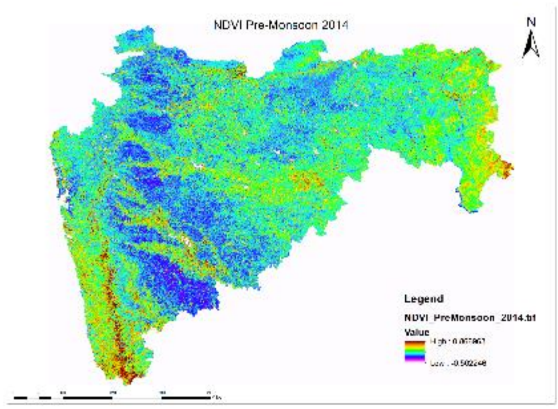
Fig 2: FCC of Pre-Monsoon a: 2014, b:2019, c:2024, post-monsoon d: 2014, e:2019, f: 2024

Vegetation and Moisture Indices

- **NDVI (Normalized Difference Vegetation Index):** Measures vegetation greenness.
  NDVI = (NIR - RED) / (NIR + RED)



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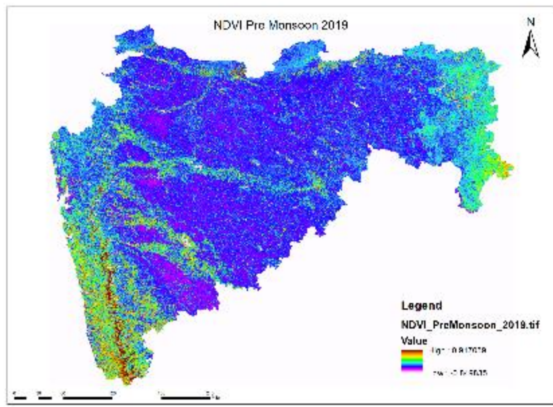

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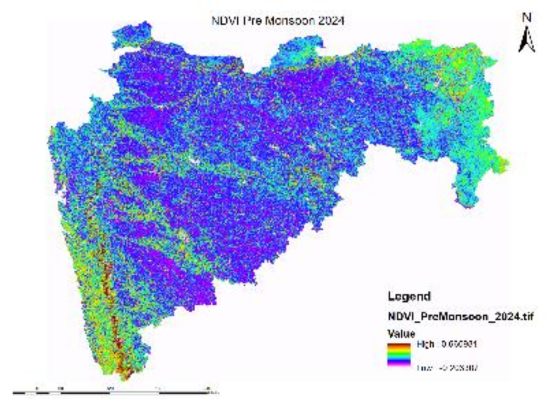

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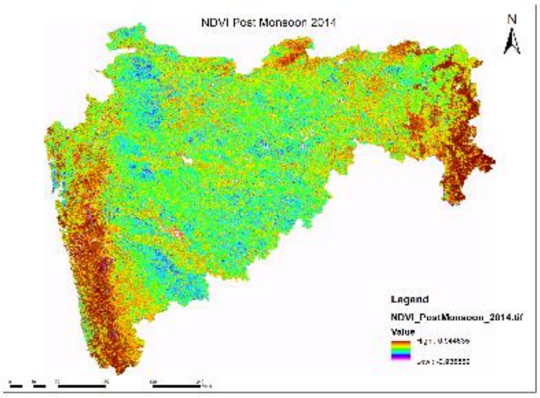

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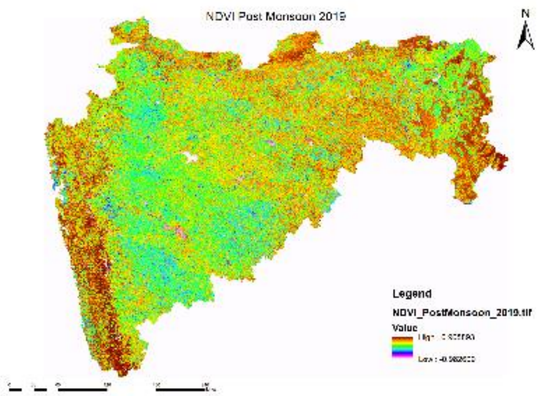

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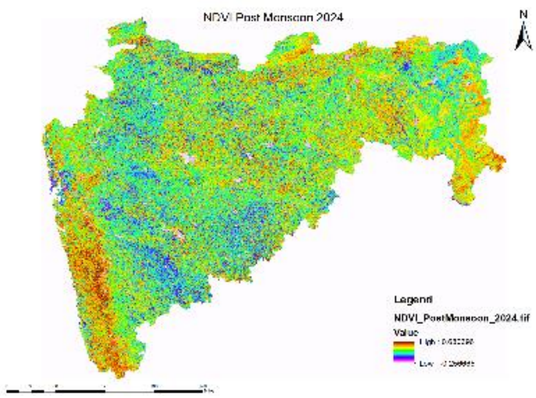

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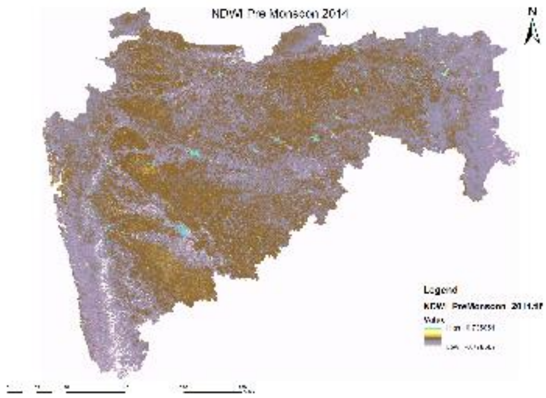
Fig 3: NDVI of Pre-Monsoon a: 2014, b:2019, c:2024, post-monsoon d: 2014, e:2019, f: 2024

- **NDWI (Normalized Difference Water Index):** Assesses vegetation moisture.
  NDWI = (GREEN - NIR) / (GREEN + NIR)



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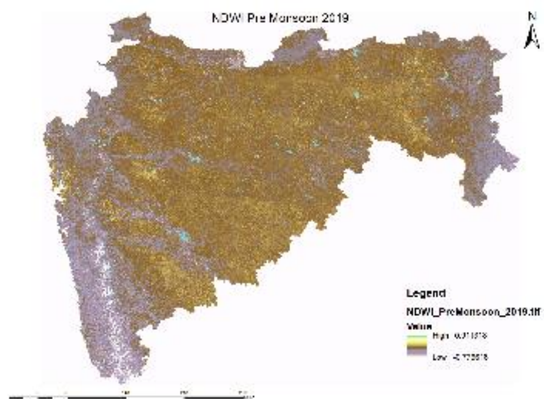

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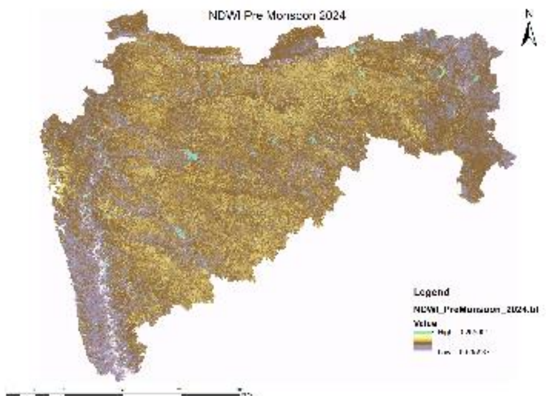

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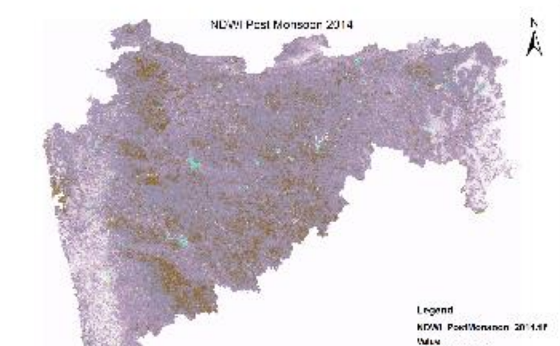

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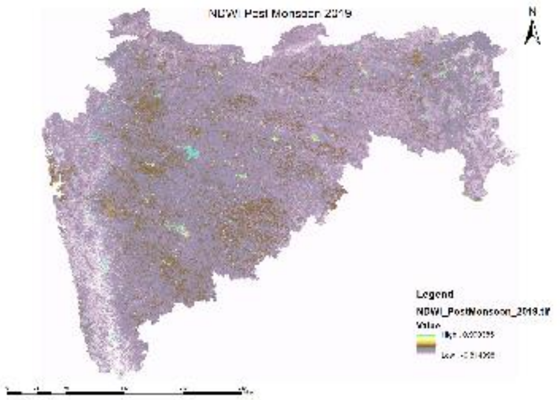

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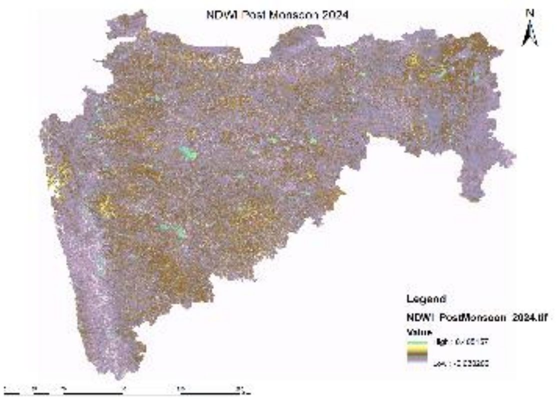

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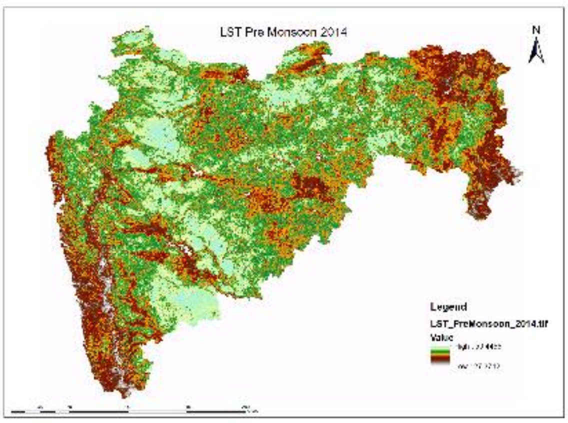
Fig 4: NDWI of Pre-Monsoon a: 2014, b:2019, c:2024, post-monsoon d: 2014, e:2019, f: 2024

- Computed for each image in the temporal series and aggregated into seasonal and annual composites.

Land Surface Temperature (LST)

- MODIS LST data integrated to detect thermal anomalies.
  $LST = BT / [1 + ((\lambda \times BT) / \rho) \times \ln(\varepsilon)]$
  Where:
  • BT = Brightness Temperature (Kelvin)
  • λ = Wavelength of emitted radiance
  • $\rho = (h \times c) / \sigma$ (h = Planck's constant, c = speed of light, σ = Boltzmann constant)
  • ε = Surface emissivity



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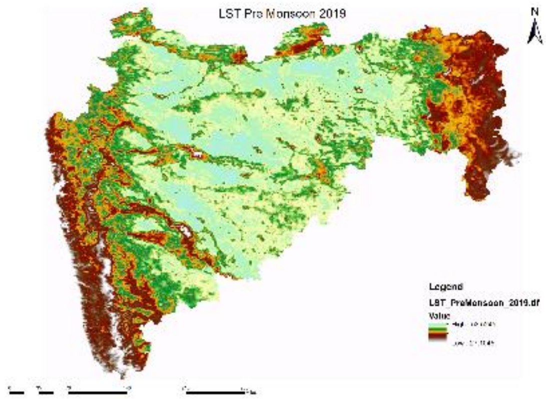

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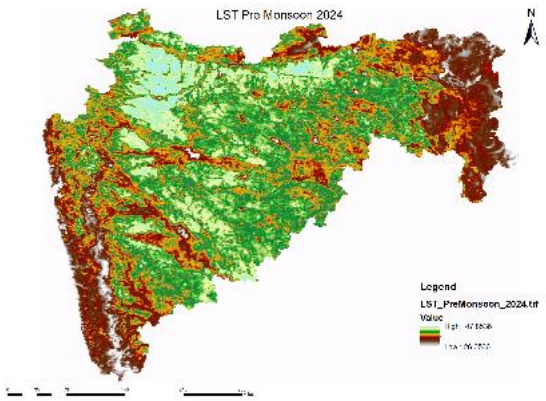

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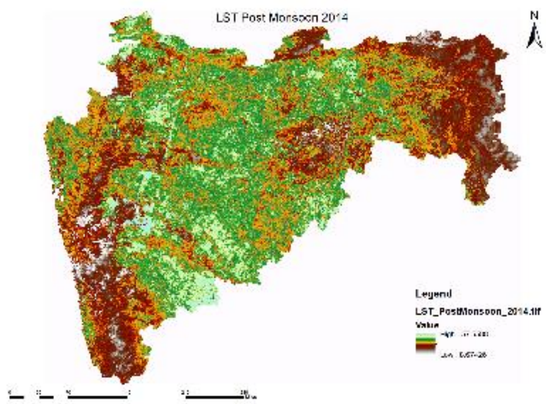

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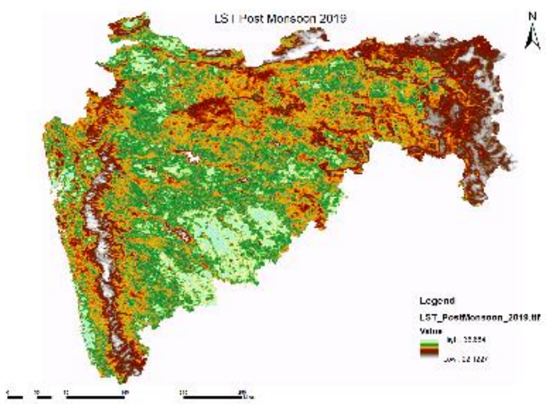

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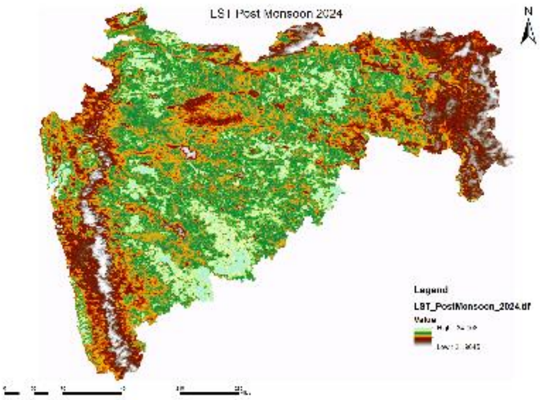

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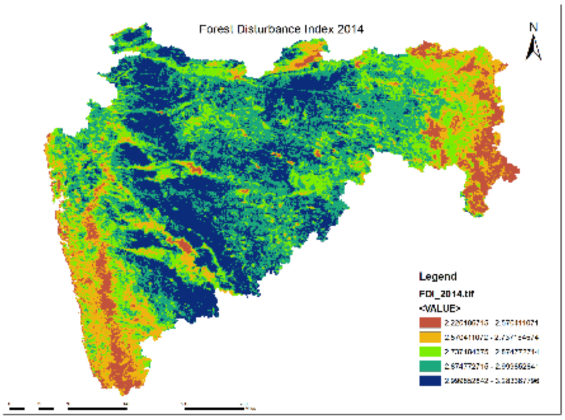
Fig 5: LST of Pre-Monsoon a: 2014, b:2019, c:2024, post-monsoon d: 2014, e:2019, f: 2024

- Seasonal mean LST calculated to identify stressed or degraded forest patches.

Forest Disturbance Index (FDI)

- FDI was developed by combining NDVI, NDWI, and LST trends.
- FDI = (1 - NDVI) + (1 - NDWI) + ((LST - 290) / 20)
- **Thresholding:** Areas with declining NDVI/NDWI and rising LST were classified as disturbed.



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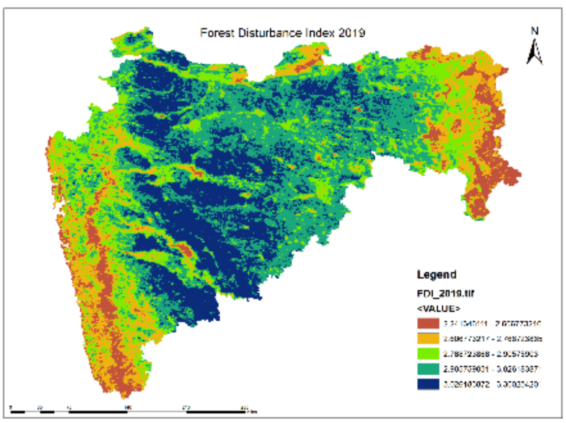

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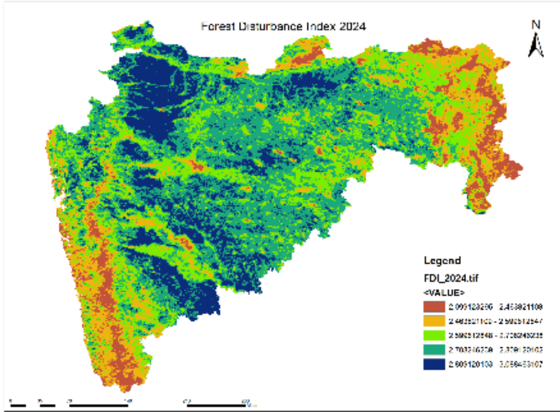

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Fig 6: Forest Disturbance Index a: 2014, b:2019, c:2024

- **Temporal analysis:** Mann-Kendall trend test and Sen's slope were applied to detect significant temporal changes.

Zonal and Spatial Analysis

- District-level zonal statistics extracted for NDVI, NDWI, LST, and FDI.
- Spatial patterns analyzed to identify hotspots of degradation and fragmentation.
- Seasonal analysis conducted to determine periods of maximum stress and recovery.

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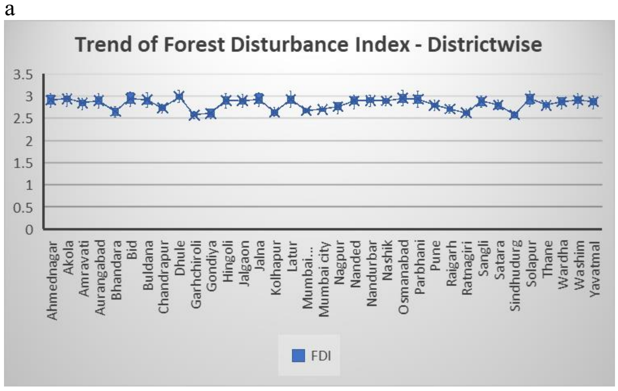

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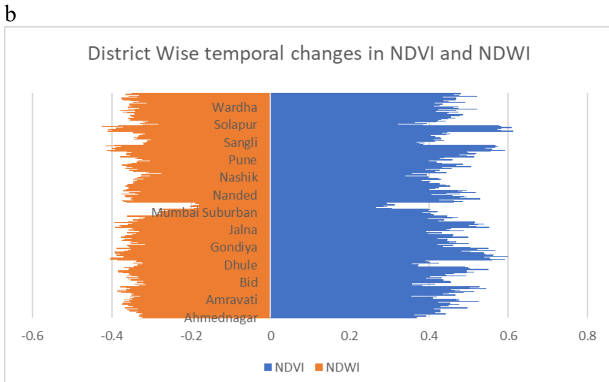

Fig 7: a: Trend of FDI- district wise, b: Trend of NDVI and NDWI- District wise

4. Results

The analysis of forest disturbance indicators across Maharashtra reveals clear spatial and temporal variations in vegetation health, thermal stress, and landscape stability. Satellite-derived vegetation indices—specifically the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water

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Index (NDWI)—showed a consistent decline of approximately 5–15% in major forested districts such as Gadchiroli, Chandrapur, and Thane over the study period. This decline was particularly pronounced during the pre-monsoon months, when vegetation experiences higher moisture stress due to elevated temperatures and limited rainfall. The reduction in NDVI and NDWI values indicates a weakening of canopy vigor and moisture retention capacity, reflecting both biophysical stress and anthropogenic pressures such as deforestation and land-use change. These patterns suggest that forest ecosystems in Maharashtra are increasingly vulnerable to seasonal droughts and climatic variability, with vegetation greenness showing only partial recovery during the monsoon season.

ADM2_NAME	Metric	Sen_slope	MK_tau	MK_p	MK_trend
Chandrapur	LST_K	-0.21048	-0.50216	0.001126	decreasing
Chandrapur	FDI	-0.01784	-0.46753	0.002442	decreasing
Chandrapur	NDWI	0.002647	0.363636	0.018737	increasing
Chandrapur	NDVI	-0.00024	-0.01732	0.932288	no trend
Garhchiroli	LST_K	-0.14693	-0.50216	0.001126	decreasing
Garhchiroli	FDI	-0.0116	-0.39827	0.009957	decreasing
Garhchiroli	NDWI	0.002936	0.363636	0.018737	increasing
Garhchiroli	NDVI	0.000247	0.051948	0.755388	no trend
Ratnagiri	LST_K	-0.20545	-0.57143	0.000207	decreasing
Ratnagiri	FDI	-0.01279	-0.57143	0.000207	decreasing
Ratnagiri	NDVI	0.001138	0.25974	0.094721	no trend
Ratnagiri	NDWI	0.000962	0.121212	0.444453	no trend
Thane	LST_K	-0.23242	-0.74459	1.28E-06	decreasing
Thane	FDI	-0.01446	-0.60606	8.26E-05	decreasing
Thane	NDWI	0.001632	0.294372	0.057752	no trend
Thane	NDVI	0.001713	0.08658	0.590495	no trend

Table 2: Mann Kendal and Sen Slope trend Analysis

Thermal analysis further highlights the growing extent of ecological stress in degraded forest areas. Land Surface Temperature (LST) exhibited an increase of approximately 1.5–2.2°C in several disturbed and fragmented patches, particularly in regions undergoing rapid land-use transitions. The rise in surface temperature is strongly associated with vegetation loss, as sparse canopies expose the ground surface to direct solar radiation, thereby intensifying local heat accumulation. This localized thermal amplification contributes to the formation of microclimatic hotspots that can disrupt natural regeneration processes and alter species composition. Elevated LST values also correspond with areas experiencing frequent forest fires, which further degrade vegetation structure and exacerbate the carbon emissions from forested landscapes.
The table below is representing the trend of FDI using the Mann Kendall and Sen slope method:

Table 3: Temporal trend analysis of FDI

Year	FDI
Jan 1, 2014	2.873
Jan 1, 2015	2.892
Jan 1, 2016	2.944
Jan 1, 2017	2.881
Jan 1, 2018	2.932
Jan 1, 2019	2.898
Jan 1, 2020	2.772
Jan 1, 2021	2.754
Jan 1, 2022	2.775
Jan 1, 2023	2.776
Jan 1, 2024	2.694

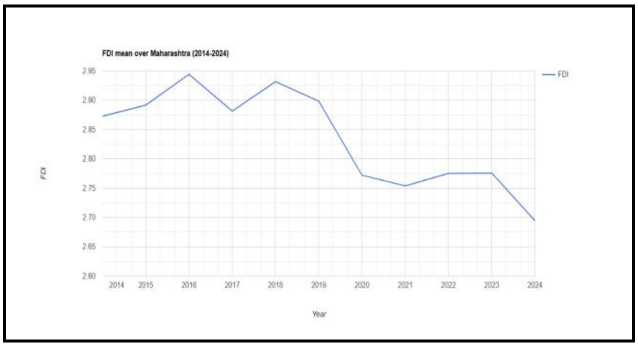

Fig 8: Trend of FDI from 2014-2024

Spatially, distinct regional patterns emerge across Maharashtra's physiographic zones. In the Western Ghats, particularly along the Sahyadri ranges, forest fragmentation is evident due to increasing encroachment, infrastructure expansion, and road development. These anthropogenic activities have led to the isolation of forest patches, disrupting habitat connectivity and reducing ecological resilience. In contrast, the Vidarbha region—encompassing districts such as Gadchiroli and Chandrapur—shows recurrent disturbance signals primarily linked to mining activities, shifting cultivation, and unsustainable extraction of forest resources. The resultant landscape heterogeneity and repeated canopy clearance have intensified the vulnerability of these ecosystems to both climatic and human-induced stresses. Meanwhile, in the Marathwada region, agricultural expansion along forest edges has created pronounced "edge effects," where the transition zones between cropland and forest exhibit signs of localized degradation. These edge zones often experience altered microclimates, reduced soil moisture, and higher exposure to invasive species, further weakening the forest structure.

Seasonal analysis reveals a cyclical pattern in forest condition throughout the year. The pre-monsoon season consistently shows maximum ecological stress, marked by high surface temperatures, reduced vegetation indices, and elevated fire susceptibility. During this dry period, water scarcity and heat stress combine to lower canopy density and increase fuel dryness, enhancing the probability of forest fires. The onset of the monsoon season brings significant recovery in vegetation greenness, as increased rainfall promotes regrowth and replenishes soil moisture. However, this recovery is often partial and temporary; by the post-monsoon period, degradation signals re-emerge in areas affected by persistent anthropogenic disturbance or poor soil resilience. This seasonal oscillation highlights the delicate balance between climatic cycles and human pressures that shape Maharashtra's forest ecosystems. Overall, the observed patterns underscore the need for region-specific management strategies that integrate land-use planning, fire risk assessment, and ecological restoration to mitigate the cumulative impacts of disturbance and sustain long-term forest health.

5. Discussion

The study demonstrates that combining multi-source remote sensing datasets allows effective detection of forest disturbances over a decade. Anthropogenic pressures, including urbanization, illegal logging, and mining, are major drivers of degradation, exacerbated by climate-induced stress such as droughts. Forest disturbances are spatially heterogeneous, with certain districts exhibiting consistent vulnerability, highlighting areas that require targeted conservation interventions.

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6. Conclusion

- Multi-temporal remote sensing provides a robust approach to monitor forest health.
- Maharashtra's forests have undergone significant degradation over the past decade, particularly in Ratnagiri, Gadchiroli, Chandrapur, and Thane as shown below from 2017-24.
- Early detection of forest disturbance hotspots is essential for planning mitigation strategies, sustainable land management, and policy formulation.
- The developed Forest Disturbance Index (FDI) offers a replicable framework for other regions experiencing similar ecological pressures.

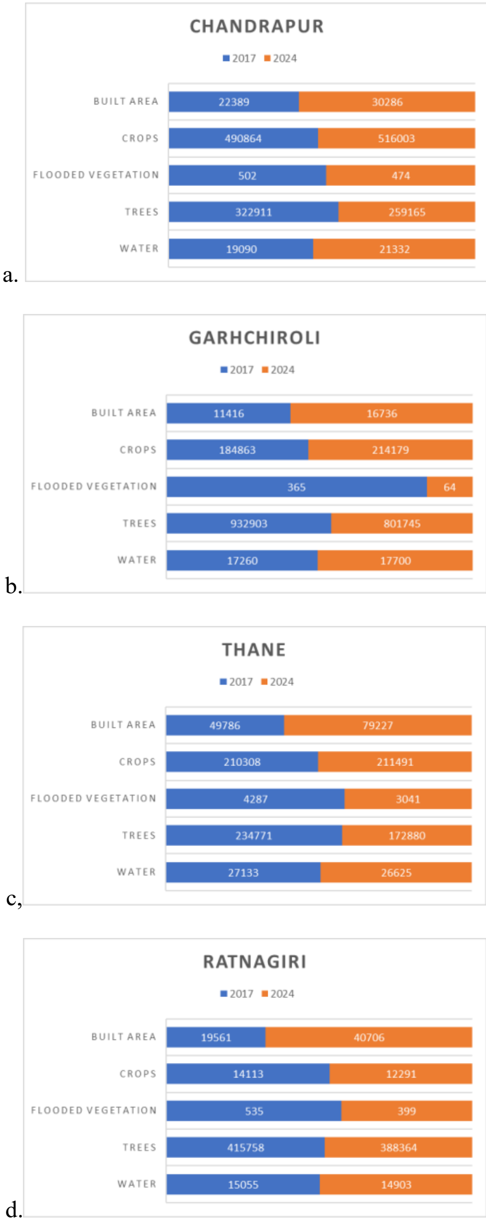

Fig 9: Classes of districts affected from2017-2024 a. Chandrapur, b. Garchiroli, c. Thane, d. Ratnagiri

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