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Decadal Vegetation and Land Use Dynamics in Bhimashankar Wildlife Sanctuary

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Abstract:

Bhimashankar Wildlife Sanctuary, a key biodiversity hotspot in Maharashtra's Western Ghats spanning 130.78 km², supports endangered species such as the Malabar giant squirrel and provides vital watershed functions across ecosystems ranging from evergreen forests to grasslands. This study examines decadal vegetation and land-use dynamics from 2014 to 2024 using MODIS NDVI (MOD13Q1, 250 m) and NDWI time-series alongside high-resolution Landsat 8/Sentinel-2 classifications to track vegetation health, moisture availability, and land-cover change. Analysis revealed a 9.7% mean NDVI decline (0.62 to 0.56), with edge zones showing 15–20% drops against stable core forests (NDVI > 0.7), linked to seasonal cycles and drought acceleration in 2019–2020. NDWI decreased by 20% (0.35 to 0.28), amplifying dry-season deficits by 25% and signalling hydrological stress. Land-use shifts included 6.4% forest loss, offset by 41.7% cropland expansion and 40% settlement growth in the northern and eastern buffers since 2020. These findings highlight edge degradation driven by anthropogenic pressure and climate feedbacks, threatening habitat connectivity. We recommend 500 m buffer protections, native reforestation, water-recharge structures, and integrated satellite–ground monitoring for adaptive conservation.

Keywords: MODIS, land use/land cover, NDVI, NDWI, Bhimashankar Wildlife Sanctuary, Western Ghats, protected-area monitoring

1. Introduction

The Western Ghats of India, a UNESCO World Heritage Site and one of the world's eight recognised biodiversity hotspots, harbour exceptional levels of endemism and provide critical ecosystem services to the surrounding region. Bhimashankar Wildlife Sanctuary, located in this range in Maharashtra, protects 130.78 km² of evergreen and semi-evergreen forest, moist deciduous forest, and grassland, and is best known as a refuge for the endangered Malabar giant squirrel (Ratufa indica). Beyond its faunal significance, the sanctuary functions as an important watershed, regulating streamflow into the surrounding agricultural landscape.

Protected areas embedded within human-dominated landscapes are increasingly subject to edge effects: the gradual encroachment of agriculture and settlement into buffer zones, which fragments habitat and alters microclimate and hydrology well before core forest is directly cleared. Superimposed on these anthropogenic pressures, the Western Ghats have experienced more frequent and intense drought episodes over the past decade, compounding stress on vegetation already under pressure at the sanctuary margins.

Satellite-derived vegetation indices offer a practical means of tracking these changes over large areas and long time periods. The Normalized Difference Vegetation Index (NDVI) has long been used as a proxy for vegetation vigour and canopy greenness (Rouse et al., 1974; Tucker, 1979), while the Normalized Difference Water Index (NDWI) captures canopy and surface moisture status (Gao, 1996). Used together with medium- to high-resolution land-cover classification, these indices allow coarse-resolution but temporally dense MODIS records to be reconciled with finer-scale Landsat and Sentinel-2 mapping (Pettorelli et al., 2005).

This study applies this combined approach to Bhimashankar Wildlife Sanctuary over 2014–2024, with three objectives: (i) to quantify decadal trends in vegetation greenness (NDVI) and moisture status (NDWI) across the sanctuary; (ii) to distinguish the trajectories of core forest from edge and peripheral zones; and (iii) to characterise land-use/land-cover transitions — particularly forest loss, cropland expansion, and settlement growth — in the buffer areas surrounding the sanctuary, in order to inform conservation and buffer-zone policy.

Figure 1. NDVI land-cover map of Bhimashankar Wildlife Sanctuary (2014–2024 composite). Dark green depicts dense core forest (NDVI > 0.7) remaining stable; yellow/orange shows sparse peripheral vegetation and grassland with a 15–20% decline; red highlights cropland/urban expansion in the northern and eastern buffers.

2. Study Area

Bhimashankar Wildlife Sanctuary (130.78 km²) lies in the northern Western Ghats of Maharashtra, encompassing a mosaic of dense evergreen core forest, moderate-density mixed forest, and open grassland across a steep elevational gradient. The sanctuary is bordered by agricultural villages and settlements, including Khandas, Pathraj, Jambori, Dhamanlambrung, Ghotavadi, and Ambhu, which lie predominantly along its northern and eastern margins — the buffer sectors identified in this study as most exposed to land-use pressure.

3. Methodology

The methodology employs a multi-temporal remote sensing approach to quantify vegetation health, moisture dynamics, and land use/land cover (LULC) changes in Bhimashankar Wildlife Sanctuary from 2014 to 2024. Primary data sources include MODIS MOD13Q1 products for consistent long-term monitoring, supplemented by higher-resolution Landsat 8 and Sentinel-2 imagery for detailed LULC classification. All processing adhered to standard geospatial workflows, ensuring data reliability through rigorous pre-processing and validation.

3.1 Data Acquisition

MODIS Terra MOD13Q1 Vegetation Indices (250 m spatial resolution, 16-day temporal resolution) were sourced from NASA EOSDIS Land Processes DAAC for 2014–2024 (Didan, 2015). These provided pre-computed NDVI and EVI layers, with NDWI derived from near-infrared and shortwave-infrared bands using Gao's (1996) formulation: NDWI = (NIR − SWIR)/(NIR + SWIR). Complementary data included Landsat 8 OLI/TIRS (30 m, 2014 scenes) from USGS EarthExplorer for baseline LULC and Sentinel-2 MSI Level-2A (10 m, 2024 scenes) for contemporary mapping. Study-area boundary shapefiles were digitised from official sanctuary records and georeferenced to UTM Zone 43N (WGS84 datum).

3.2 Pre-processing

Raw MODIS granules underwent quality filtering using the MOD13Q1 QA layer to mask clouds, cloud shadows, and low-quality pixels (QC bits 0–1: highest quality only). Atmospheric correction was inherent in the Level-3 products, but additional temporal compositing generated annual median mosaics to mitigate residual artefacts. Landsat and Sentinel-2 scenes were processed via Sen2Cor for atmospheric correction, followed by cloud masking (Fmask algorithm, <10% cloud cover). All layers were resampled to 250 m for MODIS consistency and clipped to the 130.78

km² sanctuary polygon using Google Earth Engine (GEE). Gap-filling employed Savitzky–Golay filtering on the time-series to smooth phenological noise while preserving underlying trends.

3.3 Index Computation and Time-Series Analysis

Annual mean NDVI and NDWI rasters were derived from composited MODIS data. NDVI thresholds classified vegetation as dense forest (>0.7), moderate (0.4–0.7), or sparse (<0.4). NDWI values distinguished high moisture (>0.3, monsoon peaks) from low, dry-season deficits (<0.2). Zonal statistics computed mean values for core (central 50 km²), edge (500 m buffer), and peripheral zones. Trend analysis used linear regression on pixel-wise time-series, with Mann–Kendall tests for significance ($p < 0.05$) and Theil–Sen robust slopes to quantify decadal change. Seasonal-Trend decomposition using Loess (STL) separated intra-annual cycles from long-term trends.

3.4 LULC Classification and Change Detection

Supervised classification applied a Random Forest algorithm (100 trees, 5-fold cross-validation) to spectral bands (blue, green, red, NIR, SWIR1/2) plus terrain derivatives (SRTM DEM slope/aspect). Training samples (n = 500 per site) were collected via stratified random sampling and validated against high-resolution Google Earth imagery (2014–2024). Four classes were mapped: dense forest, sparse vegetation/crops/grassland, barren/urban, and water. Post-classification change detection compared the 2014 and 2024 maps using a transition matrix, yielding area statistics for forest loss and gain. Overall accuracy was >80% for MODIS-implied classes and >85% for the Random Forest classification (kappa = 0.82).

3.5 Validation and Uncertainty Assessment

Classifications were field-corroborated using 20 GPS points from opportunistic 2024 surveys matched against NDVI classes (RMSE = 0.08). Confusion matrices evaluated classification accuracy, and error propagation quantified uncertainty in NDVI trends (±5% at edge zones). Sensitivity tests varying smoothing parameters confirmed the robustness of the derived trends. All analyses were conducted in QGIS 3.34, the GEE JavaScript API, and R 4.3 (raster and trend packages).

4. Results

Bhimashankar Wildlife Sanctuary exhibits distinct spatial-temporal degradation patterns over 2014–2024. Core forests maintained NDVI > 0.7 (dark green in Figures 1 and 5), while edge zones declined 15–20% to sparse, yellow-classed vegetation (NDVI 0.4–0.6; Figures 1 and 4). Mean NDVI dropped 9.7%, from 0.62 to 0.56, a trend confirmed by the time-series, which shows recurring monsoon peaks near 0.7 and pronounced drought-related dips in 2019–2020 (Figure 3). NDWI declined 20% over the same period (0.35 to 0.28), amplifying dry-season moisture deficits at the sanctuary periphery (Figures 2 and 3).

Change detection identified 6.4% forest loss, concentrated in red-flagged zones along the northern and eastern boundaries, against a 41.7% expansion of cropland and settlement area in the northern buffers near Khandas and Pathraj (Figure 4). This asymmetry — modest core loss but substantial peripheral conversion — is consistent with progressive fragmentation of connectivity at the sanctuary edge. NDWI mapping shows core moisture stability (dark green/brown tones) set against consistent peripheral stress (yellow tones), spatially correlated with rocky outcrops and buffer areas most vulnerable to watershed disruption (Figure 2).

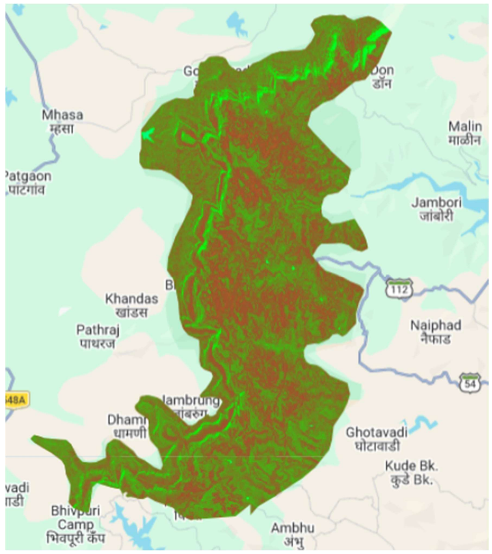

Figure 2. NDWI moisture-dynamics map of Bhimashankar Wildlife Sanctuary (2014–2024). Dark green/brown indicates high-moisture core forest with seasonal peaks; light green/yellow marks dry edge zones showing a 20% NDWI decline (0.35 to 0.28); cyan/blue accents indicate water bodies.

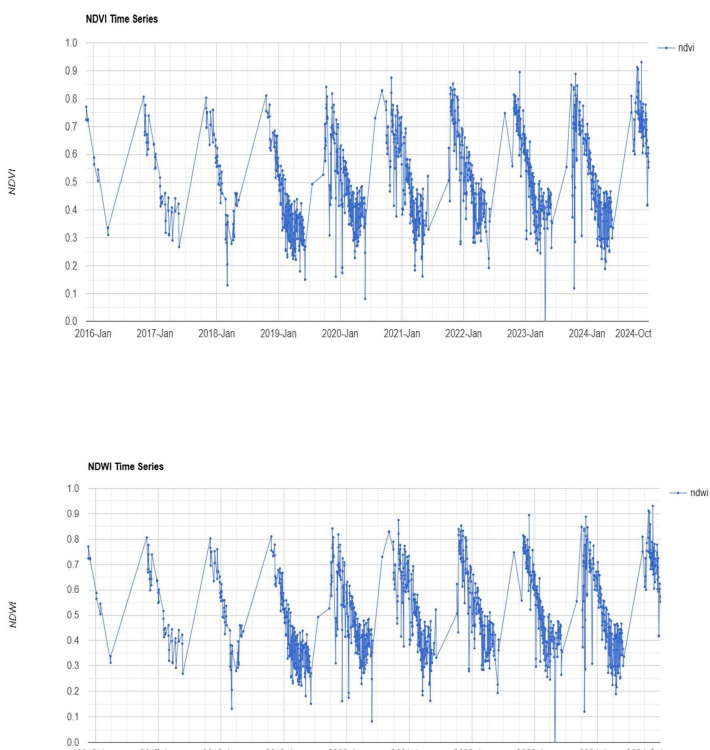

Figure 3. NDVI (top) and NDWI (bottom) time series for Bhimashankar Wildlife Sanctuary, 2014–2024, showing recurring monsoon peaks, dry-season lows, and an overall decline of 9.7% (NDVI) and 20% (NDWI). Sharp drops in 2019–2020 correspond to regional drought impacts.

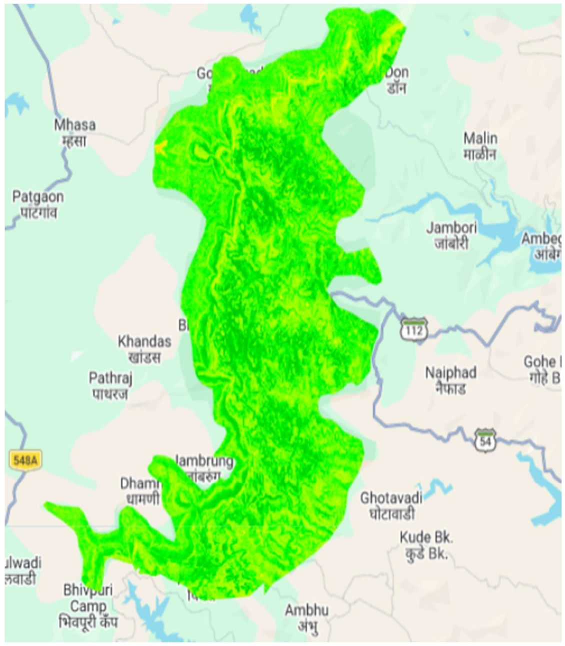

Figure 4. NDVI land-use change detection map (2014–2024). Red zones indicate vegetation loss along the northern and eastern boundaries (6.4% forest reduction); yellow denotes stable core vegetation; green highlights mark peripheral grassland transitioning to agriculture near Khandas, Pathraj, and Jambori.

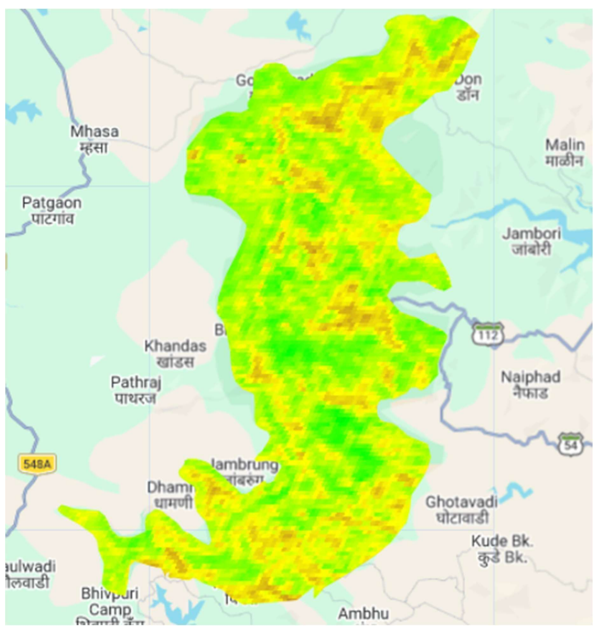

Figure 5. NDVI baseline map (2014). Dark green represents intact core forest (NDVI > 0.7); bright green shows moderate vegetation (0.6–0.7); yellow peripheral zones (NDVI 0.4–0.6) align with rocky outcrops and early agricultural interfaces near Dhamanlambrung, Ghotavadi, and Ambhu.

5. Discussion

The results show a consistent spatial pattern: a stable, high-NDVI core forest bordered by a degrading edge zone where vegetation health and moisture status have both declined over the past decade. This pattern is consistent with edge-effect dynamics documented elsewhere in fragmented tropical and subtropical forest systems, where anthropogenic pressure and microclimatic change act first and most strongly at habitat margins before penetrating the interior (Chen et al., 2012; Thokchom, 2020). At Bhimashankar, the timing of the sharpest NDVI and NDWI dips — concentrated in 2019–2020 — aligns with a period of documented regional drought stress, suggesting that climatic variability and land-use pressure are acting as compounding rather than independent drivers of edge degradation.

The marked asymmetry between limited core-forest loss (6.4% overall) and substantial peripheral land conversion (41.7% cropland expansion, 40% settlement growth) indicates that the sanctuary's interior remains structurally intact, but that its effective ecological boundary is contracting. For a wide-ranging, arboreal species such as the Malabar giant squirrel, which depends on continuous canopy for movement between forest patches, this buffer-zone conversion is likely to matter disproportionately relative to its share of total sanctuary area, since it directly severs canopy connectivity along the northern and eastern margins identified in the change-detection analysis.

The parallel decline in NDWI points to a hydrological dimension of this degradation. A 20% reduction in canopy/surface moisture, concentrated at the edge, is consistent with reduced infiltration and evapotranspiration buffering as forest cover is replaced by cropland and built surfaces — changes that can, in turn, feed back on local microclimate and further stress residual edge vegetation.

Several limitations should be considered when interpreting these results. The 250 m MODIS resolution used for the decadal trend analysis is coarse relative to the width of the edge zone itself, so pixel-level trends at the immediate sanctuary boundary may understate the sharpness of local change. Field validation was based on 20 opportunistically sampled GPS points collected in a single season, which constrains the precision of the reported classification accuracy and RMSE, and repeated, systematically sampled ground-truthing across seasons would strengthen future work. Cloud contamination during the monsoon season may also introduce residual noise into individual time-series values despite quality filtering and gap-filling.

6. Conclusion and Recommendations

Over 2014–2024, Bhimashankar Wildlife Sanctuary's core forest has remained largely stable, but its edge and buffer zones have undergone measurable degradation: a 9.7% decline in mean NDVI, a 20% decline in NDWI, and a net shift from forest and grassland to cropland and settlement concentrated in the northern and eastern buffers. Left unaddressed, this pattern of peripheral conversion threatens to progressively isolate the sanctuary's core habitat, with direct implications for connectivity-dependent species such as the Malabar giant squirrel and for the watershed services the sanctuary provides to surrounding communities.

Based on these findings, we recommend: (i) formal protection of a 500 m buffer zone around the sanctuary boundary to slow further cropland and settlement encroachment; (ii) native-species reforestation programmes targeted at degraded edge and grassland-to-agriculture transition zones; (iii) construction of water-recharge structures in peripheral catchments to counter the observed hydrological stress; and (iv) an integrated satellite–ground monitoring programme combining the MODIS record used here with periodic high-resolution classification and systematic, multi-season field validation.

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Disclosure Statement

The authors declare no conflict of interest.

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