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RESEARCH ARTICLE

An Integrated Forest Threat Assessment in Kali Tiger Reserve Western Ghats Using Multi-Source Multi-Temporal Data (1972–2023)

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Abstract

Assessing multiple forest threats through satellite remote sensing datasets helps better understanding of the ecosystem integrity, especially in protected areas (PAs). Such integrated assessments are scarce for the Kali Tiger Reserve (KTR) in the Western Ghats. In this context, this study addressed the major disturbance regimes by combining deforestation (1973–2023), fragmentation (2023), fires (2012–2023), and mono-plantations. Multi-source, multi-temporal satellite datasets, including Landsat series imagery, Sentinel-2A (10 m), topographical maps, decadal Suomi-NPP fire data, and in situ observations, were used for the threat assessment. A hybrid classification (digital and visual) technique was employed to quantify individual threats. Results were visualised at a 1 km^2 grid for systematic understanding and identification of various risk zones. About 6.7% of the grids experienced deforestation mainly due to dams and recent landslides, 16.6% by forest fires, 8.9% by mono-plantations, and 78.7% by fragmentation. From the integrated forest risk map, approximately 16% of grids were identified as a very high-risk class, 49.4% under a moderate risk, and 33.4% were classified as low risk. The results were validated through stratified random sampling points across the landscape, field observations, and ancillary data with user accuracy of 0.96 and a Kappa value of 0.92. The proposed methodology offers a replicable framework for prioritizing conservation efforts and ensuring the sustainable management of protected areas.

Keywords Kali Tiger Reserve · Western Ghats · Multi-threat hotspots · Forest risk zonation

Introduction

Up-to-date information on the conservation status of protected areas (PAs) is essential for maintaining biodiversity, ecological integrity, and ecosystem services (Costanza et al., 1997; Wang et al., 2024; McCarthy et al., 2021). Historically, various natural and human-induced pressures hinder conservation efforts in many parts of the world, and India is not exceptional (Hoffmann, 2022; Bawa et al., 2021). Systematic monitoring of ecologically significant areas is important for developing holistic conservation strategies. In a biodiverse and maga-populous nation like India, this is essential to address the major conservation challenges, including tree loss, deforestation, fires, invasive species, shifting cultivation, and mono-plantations (Pasha & Dadhwal, 2024; Reddy et al., 2016; Roy, 2003; Pasha & Reddy, 2024; Pasha et al., 2020; Swarada et al., 2024a).

Under the Wildlife Protection Act of 1972, protected areas (PAs) were established in India for biodiversity conservation (Ekka et al., 2022). The Western Ghats Biodiversity Hotspot (WGBH) of India has 39 PAs, which include 10 Tiger Reserves, 9 National Parks, and 20 Wildlife Sanctuaries protecting unique flora and fauna (www.ntca.gov.in; www.worldheritageoutlook.iucn.org; www.wiienvis.nic.in; www.world-heritage-datasheets.unep-wcmc.org). Several studies have shown that the Western Ghats Biodiversity Hotspot has been adversely affected by multiple

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ecological pressures, including deforestation, fragmentation, and climate change, threatening biodiversity and disrupting ecosystem functioning (www.ntca.gov.in; Munoz et al., 2021; Reddy et al., 2016; Yunus et al., 2021; Pasha & Dadhwal, 2024). In the Western Ghats (WG), dams, expansion of agriculture and plantations, and infrastructure development are major drivers of deforestation (Sudhakar et al., 2015; Reddy et al., 2016; Kissinger et al., 2012; Munoz et al., 2021). Approximately 35.3% of the forest cover in the Western Ghats Biodiversity Hotspot was lost between 1920 and 2013 due to deforestation driven by an expanding human footprint, land-use/land-cover (LULC) change, mining, forest fires, and infrastructure development (Reddy et al., 2016; Yunus et al., 2021). These drivers result in landscape fragmentation, whereby continuous forest landscapes are divided into smaller, isolated patches by anthropogenic activities and natural processes, leading to ecological degradation (Sudhakar et al., 2015; Vogt et al., 2007; Bogaert et al., 2011; Reddy et al., 2014). Particularly in PAs fragmentation is a critical indicator of ecological degradation (Sudhakar et al., 2015; Chaudhary et al., 2022). Because fragmentation studies often focus only on terrestrial forests, hence quantification of fragmentation across the entire natural landscape, including water bodies, considering the landscape heterogeneity and ecosystem services (Qiu & Mitchell, 2024).

Forest fires are a significant environmental threat, particularly caused due to both natural factors, such as lightning and friction from rolling stones, and human activities, including shifting cultivation, clearing paths, and covering up illicit tree felling (Srivastava & Garg, 2013; Jodhani et al., 2024; Badarinath et al., 2006; Dennis et al., 2002). In India, nearly 90% of vegetation fires are anthropogenic, with surface fires predominantly affecting tropical dry deciduous forests (Srivastava & Garg, 2013; Joseph et al., 2009; Negi, 1986; Roy, 2003). While controlled burns within PAs are occasionally used to manage forest health (Brodie et al., 2024; Kumar, 2019), when uncontrolled these fires pose serious risks to biodiversity, ecosystem integrity, and nearby human settlements (Jaffe et al., 2020; Dennis et al., 2002). Such disturbances often lead to deforestation and habitat fragmentation in ecologically sensitive regions.

Although plantations are often established as part of ecological restoration programmes, mono-plantations within protected areas are widely recognised as ecologically undesirable (Ramachandra et al., 2017; Saravanan, 2018; Mahmud et al., 2018; Bond et al., 2019; MoEFCC, 2023). Recent findings show that teak and eucalyptus plantations in the Rajiv Gandhi (Nagarhole) Tiger Reserve (RTR) have failed to transition into natural forests even after a century (Swarada et al., 2024a).

There is broad scientific consensus that forest ecosystems face significant biodiversity loss due to anthropogenic disturbances such as habitat fragmentation, invasive alien species, and forest fires, which in turn drive forest degradation (Gadgil, 1990). Most ecosystems across India are subjected to multiple interacting drivers of ecological change (Reddy et al., 2017). Hence, there is a need to evaluate the integrated impact of multiple drivers on natural ecosystems to enhance scientific understanding and inform strategies for mitigating forest stress, conserving biodiversity, and addressing climate change (Reddy et al., 2017). To evaluate and manage such threats, integrating technology and the use of spatial data is recognised in several national and international frameworks to ensure that PA meet their conservation objectives (National Wildlife Action Plan 2017-31: www.wii.gov.in; Convention on Biological Diversity: www.cbd.int; CIFOR-ICRAF:www.cifor-icraf.org; PAME: www.protectedplanet.net). For landscape-level quantification and assessment, Geographic Information System (GIS) and remote sensing (RS) technology, provide a reliable, scalable, and cost-effective approach. Monitoring of ecosystems only through ground-based surveys is impractical for larger spatial scales, because they require extensive data collection over large spatial and temporal scales and are both time- and resource-intensive (Reddy et al., 2017). Geospatial analysis has become central to conservation planning, enabling site prioritization based on habitat status (Roy, 2003). Integrated approaches have enhanced the utility of remote sensing in natural resource management, with satellite-derived data combined with field observations offering a robust framework for identifying ecosystems under varying levels of threat (Reddy et al., 2017).

State level integrated forest threat evaluation was carried out for Odisha and Telangana at 5 km^2 grid (Reddy et al., 2014; Sudhakar et al., 2015). In the context of PAs, Saranya and Reddy (2016) analysed long-term forest cover changes in the Similipal Biosphere Reserve at a 1 km^2 scale. Similarly, studies by (Ramachandra et al., 2017, 2018) investigated landscape transitions in the WG of Karnataka, focusing on individual aspects. Literature indicates a lack of comprehensive multi-threat ecosystem-based evaluations at finer scales, particularly in PAs of the WG. Therefore, the present study employs a comprehensive approach to identify, measure, and assess the changes and threats to KTR over the past five decades using satellite imagery, ancillary datasets, and in situ observations.

While previous studies on KTR have focused on individual aspects such as biodiversity, ecosystem threats, and land use dynamics, the present study addresses this gap by conducting a multiple threat assessment. This integrated approach captures cumulative impacts and cascading ecological effects that are often overlooked in single-threat assessments. By addressing discrepancies in the definitions of forest and tree loss and quantifying landscape fragmentation across natural landscapes, not just terrestrial forests, this assessment ensures a more robust and unbiased evaluation (Reddy et al., 2016; Pasha & Dadhwal, 2024; Bogaert et al., 2011).

In this context the current research aims to understand: (1) Spatio-temporal mapping of various disturbances regimes viz. deforestation, landscape fragmentation, forest fires and mono-plantations using multi-source and multi-temporal data; (2) Grid-based risk assessment using various disturbance regimes in the forest ecosystem of KTR and (3) Identification of sites experiencing multiple threats for targeted conservation efforts.

Study Area

The KTR, located within the ecologically significant Western Ghats, is situated in Uttar Kannada district of Karnataka state (Fig. 1). KTR lies between latitudes 14 ° 57' 23.04'' N; longitudes 74° 15' 7.56'' East and latitude 15°9'56.16'' North; longitude 74 °43' 10.56'' East covering an area of 1425.84 km^2 as per boundaries provided by Karnataka Forest Department. It was declared as the Dandeli-Anshi Tiger Reserve in 2007 by merging two PAs, Anshi National Park (established in 1987) and Dandeli Wildlife Sanctuary (established in 1956), later renamed as KTR in December 2015. As per the Tiger conservation plan 2008, it harbours over 272 species of birds, 66 species of reptiles, and 33 species of amphibians. It connects the Cotigao, Netravali, Bhagwan Mahaveer Wildlife Sanctuaries, and Mollem National Park in Goa to the west; Bhimgad Wildlife Sanctuary to the north; and the Sharavathi Valley and Kudremukh-Bhadra complex to the south, ensuring ecological continuity and tiger gene flow across the Western Ghats. It hosts endemic species like the Southern Birdwing, Malabar Tree Nymph, Tiger, and Leopard, along with 272 bird species, including the Great Pied Hornbill and Ceylon Frogmouth. It is the catchment area for the Kali River and its tributaries. Rainfall ranges from 1250 mm to 4000 mm, averaging 2500 mm annually, and decreases from west to east. Temperatures vary between 16 and 36 °C year-round. Elevation spans from 2 m to 1046.55 m, with clayey, humus-rich, well-drained soil supporting good forest growth. As per Champion and Seth (1968) vegetation types present here are South Indian Moist Deciduous Teak Forests (3B/C1), Southern Moist Mixed Deciduous Forests (3B/C2); West Coast Semi-Evergreen Forests (2A/C2), Moist Bamboo Brakes (2B/E3) and Cane Brakes (2B/E1) (Champion & Seth, 1968). The plant species mainly include *Tectona grandis*, *Terminalia paniculata*, *Xylia xylocarpa*, *Lagerstroemia microcarpa*, *Dalbergia latifolia*, *Syzigium cuminii and Macaranga peltata* (Kulkarni & Hegde, 2015). The details of the study area are depicted in Fig. 1).

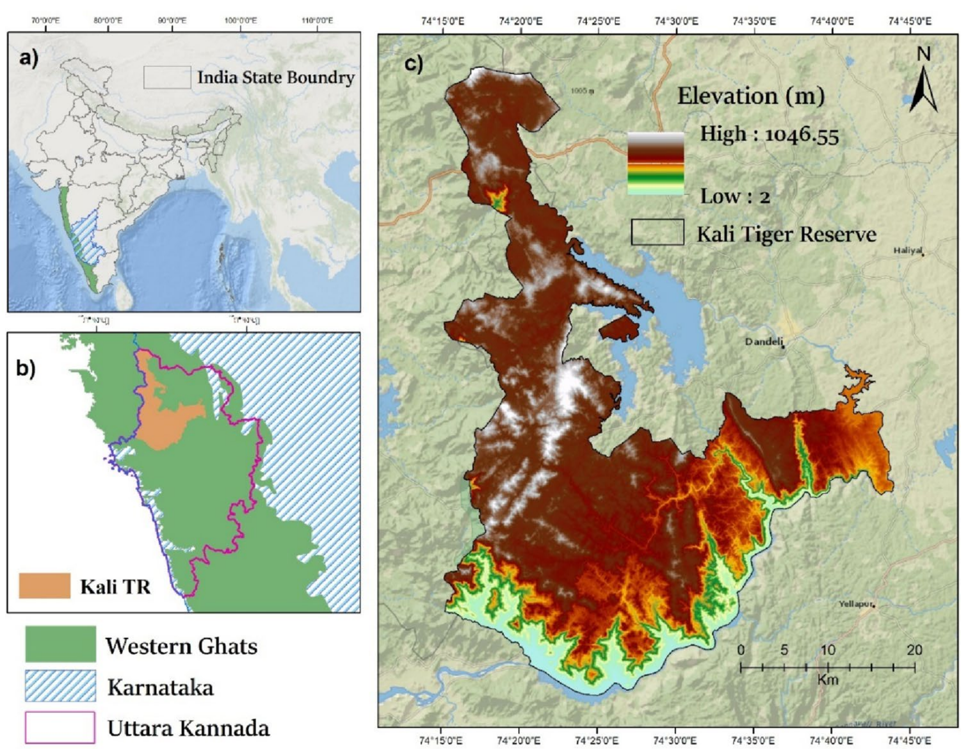

Fig. 1 Map representing **a** India showing the location of Karnataka state and Western Ghats, **b** Uttar Kannada district with Kali Tiger Reserve, and **c** Kali Tiger Reserve with elevation details

Materials and Methods

Data Utilised

Multi-spectral satellite images from the Landsat series and Sentinel program (U.S. Geological Survey and the European Space Agency) were used, selecting datasets with minimal cloud cover for 1973, 1993, 2003, 2014, and 2023. Ancillary datasets for reference to improve LULC, such as digital elevation model data from the Shuttle Radar Topography Mission (SRTM GL1), very high-resolution (VHR) imagery from Google Earth Pro, the Survey of India (SOI) topographical maps, and global building footprints, were utilized. Building footprint data was sourced from Cornell University's open Buildings dataset, developed by Google Research using a U-Net deep learning model for pixel-wise segmentation (Sirko et al., 2021). The details of these datasets with their sources are provided in Table 1. Geo-coordinates were collected from selected field sites, principally landslide-affected areas and plantation sites, chosen to represent the major disturbance regimes assessed, for use as ground-reference and validation points.

Land Use Land Cover Classification

Multi-temporal Landsat and Sentinel satellite imagery was used for land use/land cover (LULC) classification. Images with minimal cloud cover and georeferenced Survey of India (SOI) topographical maps were selected for the analysis. Band compositing and mosaicking were performed to generate true-colour and false-colour composites, which were subsequently clipped to the study area for spatial analysis and visualization. Image processing and analysis were carried out using ERDAS Imagine 2015, ArcGIS 10.8, and QGIS.

A hybrid classification approach, integrating both digital and visual interpretation techniques, was adopted to improve classification accuracy in the heterogeneous landscape of the study area (Sader et al., 1995; Ozesmi & Bauer, 2002). Initially, unsupervised classification was performed using the K-Means clustering algorithm in ERDAS Imagine, generating 200 spectral clusters. These clusters were subsequently refined and interpreted using very high-resolution (VHR) Google Earth imagery, SOI topographical maps, global building footprint data (Sirko et al., 2021), and field observations. The refined clusters served as the basis for assigning final LULC classes and were validated using ground-reference data and ancillary datasets.

The final LULC classes comprised natural forest, agriculture, water bodies, built-up, landslides, areca plantations, teak plantations, and others. The "Others" class included barren and rocky areas that could not be assigned to any of the other LULC categories.

Following Reddy et al. (2016), natural forest was defined as land greater than 1 ha dominated by native (non-planted) tree species with an overstorey canopy cover exceeding 10%. Natural forests were distinguished from plantations using the hybrid classification approach supported by multi-source reference datasets, topographical maps, and field observations rather than by direct species identification from satellite imagery.

Monitoring Long-Term Deforestation (1973–2023)

Deforestation, defined here as the conversion of forest to non-forest LULC classes (Supplementary Table S2), was analysed over the past five decades using classified raster images from 1973 to 2023 in ERDAS. Forest loss due to fire was not included in this layer, as burned areas generally recover in subsequent seasons; fire is assessed separately as an independent threat. The Matrix Union function generated an output raster showing overlaps between forest and non-forest classes, creating a detailed spatial map of deforestation patterns. Area calculations for forest-to-non-forest

Table 1 Details of the multi-source and multi-temporal data used

Satellite/sensor	Date of pass	No of tiles	Spatial resolution (m)	Source
Landsat MSS	2-Mar-1973	1	80	https://earthexplorer.usgs.gov
Landsat TM	15- Feb-1993	1	30	
Landsat ETM+	19-Feb-2003	1	30	
Landsat OLI	9-Feb-2014	1	30	
Sentinel-2 A	19-Feb-2023	2	10	https://dataspace.copernicus.eu
Sentinel-2 A	5-March-2023	2	20	
VIIRS (Suomi-NPP)	2012 to 2023		375	https://firms.modaps.eosdis.nasa.gov
Ancillary data				
Survey of India Toposheets	2005		1:50000	https://onlinemaps.surveyofindia.gov.in
SRTM GL1	February 2000		30	https://opentopography.org/
Open Buildings Dataset	2021		0.5–1	Sirko et al. (2021) https://sites.research.google/gr/open-buildings/
Google Earth Images	2014 and 2023		0.3–15	https://earth.google.com
Open Street Map (OSM)	2018			www.gisenglish.geojamal.com

transitions enabled precise quantitative analysis of land cover dynamics. The generated output was converted to a shapefile.

Identification and Mapping of Mono-plantations

Accurate discrimination between mono-plantations and natural forests is challenging because of spectral similarity and mixed spectral responses in satellite imagery. To overcome this limitation, mono-plantation areas were manually digitized as a separate land-use class using 2023 very high-resolution (VHR) Google Earth imagery, supported by field observations and ancillary reference data. Polygon boundaries were digitized at a mapping scale of 1:200–1:300, exported as Keyhole Markup Language (KML) files, and subsequently converted to shapefile format. The shapefiles were then reprojected to the Universal Transverse Mercator (UTM) Zone 43 N coordinate system for subsequent spatial analysis and mapping.

Identification of Disturbed Forests

Delineation of Natural and Human-modified Landscapes

LULC classification from 1973 to 2023 defined natural (forest, water) and anthropogenic (agriculture, built-up, plantations) landscapes within the TR. Forest-to-non-forest conversions were categorized as anthropogenic, while comparatively undisturbed, unchanged areas remained natural, reflecting ecological stability and human-induced changes. OpenStreetMap (OSM) -derived data delineated the road network, with average widths determined using the Ministry of Road and Transport's Road Statistics of India 2018-19 report and OpenStreetMap. ArcMap 10.8 software was utilized to apply buffer to categorize areas under anthropogenic landscapes.

Modeling Landscape Fragmentation (2023)

Fragmentation refers to the division of a continuous landscape with large, interconnected patches into smaller, isolated patches that are more numerous and less connected (Sudhakar et al., 2015). The Landscape Fragmentation Tool (LFT 2.0) offers scalable, pixel-level precision for quantifying fragmentation (Vogt et al., 2007; Ostapowicz et al., 2008). Present study employed LFT 2.0 for detecting and quantifying the fragmentation within the natural landscape. This tool identifies the specific types of fragmentation occurring within a targeted land cover. The fragmented land cover is classified into core (interior forest pixels far from the forest edge); perforated (forest pixels on the edge of a small inside non-forest area); edge (pixels between forest and large non-forest areas); and patch (pixels between forest and large non-forest areas) (forest patches too small to accommodate core forest). Furthermore, based on the size of a given core patch, the core regions are divided into three size classes: core-1 ($<$100 ha), core-2 (101–202 ha), and core-3 ($>$202 ha) (Vogt et al., 2007; Reddy et al., 2018).

Delineation of Disturbed Areas

The Landscape Fragmentation analysis classified areas into patch, edge, perforated, and core categories. For this study, regions identified as patch, edge, and perforated were reclassified as disturbed landscapes, while core areas (small, medium, and large) were designated as undisturbed landscapes. The results were exported as a shapefile for further spatial analysis.

Analysing Decadal Forest Fires (2012–2023)

Globally, NASA's FIRMS provides near real-time active fire data from MODIS and VIIRS sensors, widely used for wildfire monitoring and management. VIIRS, with its higher spatial resolution and enhanced thermal detection via infrared bands, is particularly effective for tracking smaller or fast-moving fires (Coskuner, 2022). VIIRS (Suomi-NPP) satellite data were used to identify fire locations, seasons, and occurrences in the TR from 2012 to 2023, and were validated with Sentinel-2 A images. The Hotspot Analysis tool (Getis-Ord Gi*) detected fire-prone areas by identifying statistically significant spatial clusters. High-value clusters were classified as hotspots, and low-value clusters as cold spots, using z-scores and p-values to determine statistical significance. This analysis helps identify areas of concentrated activity (hotspots) or inactivity (cold spots) for targeted action and further investigation.

Grid-Wise Multi-Threat Analysis

The current study has attempted to utilize a holistic grid-based monitoring approach to identify areas that experience multiple environmental threats within the reserve. This involves dividing a geographical area into uniform spatial units (grids) to systematically collect, analyse, and monitor data that ensures effective decision-making (Kumari et al., 2023). This approach has proven robust for detecting various ecological changes at different scales (Reddy et al., 2014; Sudhakar et al., 2015; Paul & Banerjee, 2021). Grid-based monitoring approaches using a 1 km^2 grid have proven advantageous for capturing small-scale disturbances such as deforestation and habitat loss. It aligns with the increasing availability of high-resolution spatial data, enabling managers to track ecological trends accurately over time and space.

Table 2 Details of grid categorization by area-determined threat intensity

Type of threat	Category	Grids with area (Hectares)
Deforestation	High	> 50
	Moderate	10–49.9
	Low	< 10
	Very low	< 30
Disturbed areas	Very high	> 40%
	High	20–40%
	Moderate	10–20%
	Low	< 10%
Fire hotspots	Very high	Presence of fire hotspots
Mono-plantations	High	20–100
	Moderate	10–20
	Low	< 10

A 1 km² grid system was created using ArcMap 10.8 for uniform spatial analysis. Each grid cell was evaluated for threats such as deforestation, fragmentation (disturbed and undisturbed areas), forest fires, and mono-plantations. This grid-based approach ensured precise threat quantification across the landscape. Threat layers were overlaid onto the grid, and each cell was assessed for threat presence and intensity. The cumulative impact within each grid was calculated by integrating threat values, categorizing grids into very high, high, moderate, and low-risk levels based on specific threat area values. Details of threats, grid categorization, and criteria are provided in Table 2.

Grids with landslide-driven vegetation loss were classified as high-risk zones due to increased susceptibility to future landslides. This spatially precise evaluation identified multi-threat hotspots by analyzing grids with overlapping threats. Categories were assigned based on aggregated threat values from deforestation, fragmentation, mono-plantations, and forest fires. Very high-risk zones had threat values of 16–20, high-risk zones 10–15, moderate-risk zones 5–9, and low-risk zones below 5. The overall methodology is depicted in Fig. 2.

Results

The study assessed four major forest threats in the Kali Tiger Reserve (KTR), namely deforestation, landscape fragmentation, forest fires, and mono-plantations. For the analysis, the reserve was divided into 1,642 grid cells, each measuring 1 km². Based on the predefined area-based thresholds (Table 2), each grid was evaluated for the intensity of individual threats and subsequently classified into Very High, High, Moderate, and Low risk categories.

Deforestation

The analysis revealed that 111 grid cells (6.7% of the total) experienced deforestation during the period 1973–2023,

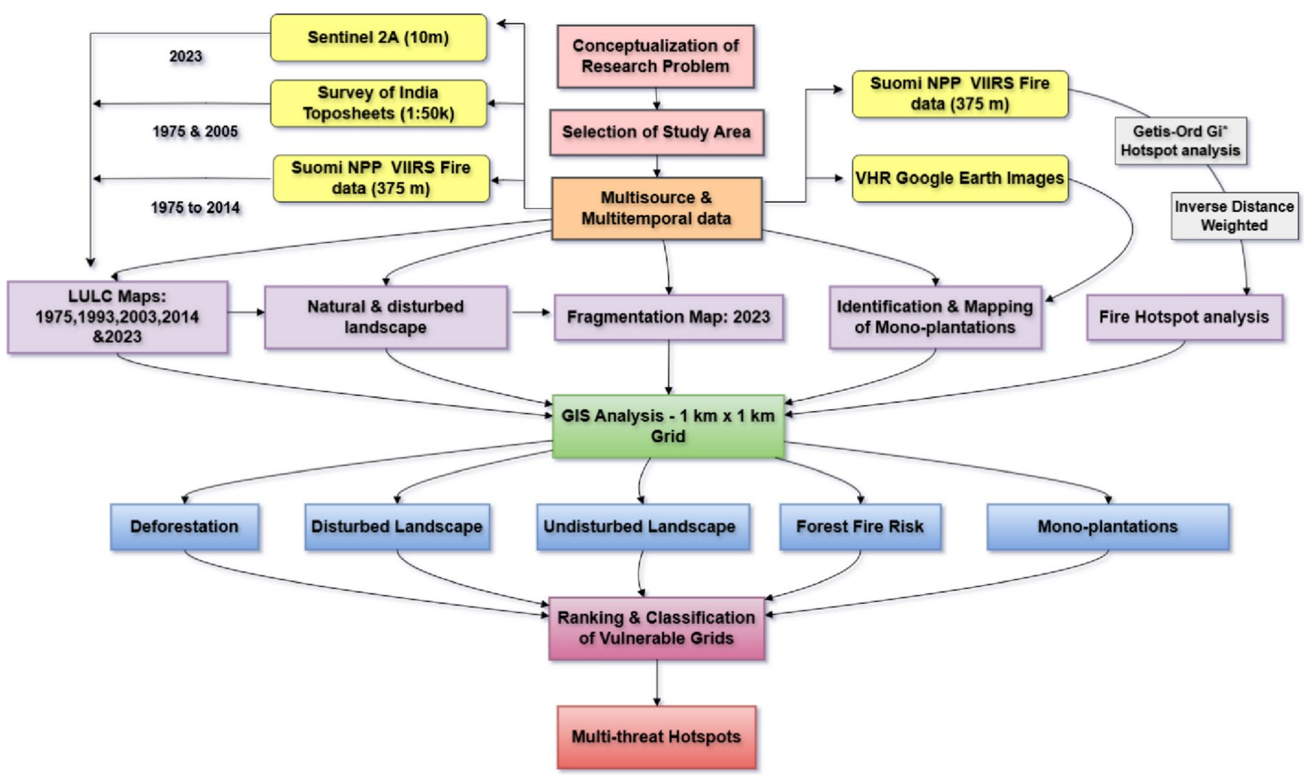

Fig. 2 Flowchart illustrating the overall methodological framework adopted in the study

predominantly in the southern part of the Kali Tiger Reserve (KTR). The observed forest loss was primarily associated with landslides and the construction of the Kadra, Kodasalli, and Bommanahalli dams (Fig. 3). It is noteworthy that the Kadra Dam was constructed prior to the declaration of the area as a Tiger Reserve.

A total of 1,416.67 ha of forest was converted to non-forest land during the study period. Of this, 178.17 ha occurred in 35 low-risk grids, 842.46 ha in 32 moderate-risk grids, and 396.04 ha in 44 high-risk grids (Fig. 4).

Disturbed Forest

The natural landscape of the Kali Tiger Reserve (KTR) covers approximately 1,299 km², while 128 km² comprises human-modified landscapes, including agriculture, settlements, plantations, roads, and landslides. Landscape fragmentation analysis revealed that 1,292 grid cells (78.68%) were affected by fragmentation associated with both natural and anthropogenic disturbances. Overall, approximately 14.2% of the natural landscape exhibited fragmentation, primarily resulting from agricultural expansion, settlements, transportation infrastructure, landslides, and mono-plantations.

A total of 18,530.62 ha of the study area was classified as disturbed. Of this, 2,677.69 ha (531 grids) was categorized as Low, 6,180.70 ha (413 grids) as Moderate, 9,059.30 ha (334 grids) as High, and 612.91 ha (14 grids) as Very High disturbance (Fig. 5).

Forest Fires

The primary fire season in the KTR extends from January to April, during which the majority of fire incidents were recorded. Over the study period (2012–2023), fire activity exhibited considerable interannual variation, peaking in 2016, followed by a decline in subsequent years and a slight resurgence in 2023 (Fig. 6). Most fire occurrences were concentrated in the eastern part of the reserve, where the landscape is predominantly human-modified and comprises agricultural lands, human settlements, mono-plantations, and a dense tertiary road network.

The concentration of built-up areas in the eastern region is likely associated with the high frequency of anthropogenic

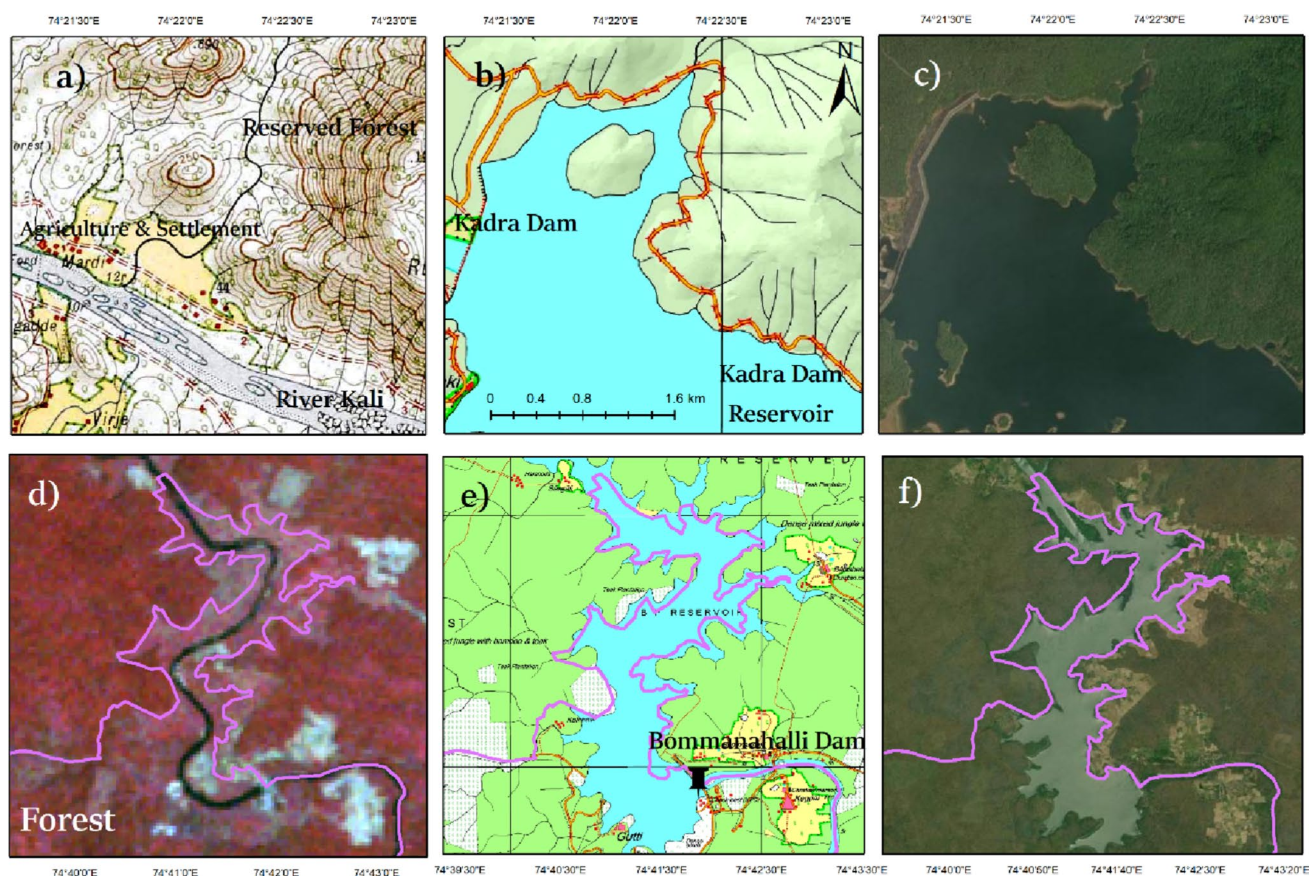

Fig. 3 Land-cover changes around the Kadra and Bommanahalli dams, presented as an interpretive comparison using multiple data sources: **a** topographical map (1932; 1:63,360), **b**, **e** Survey of India topographical maps (2005; 1:50,000), **c** ArcGIS Online World Imagery basemap (12 August 2023), **d** Landsat image (19 January 1976), and **f** ArcGIS Online World Imagery basemap (20 March 2024). The pink outlines in panels **d–f** indicate the boundary of the KTR

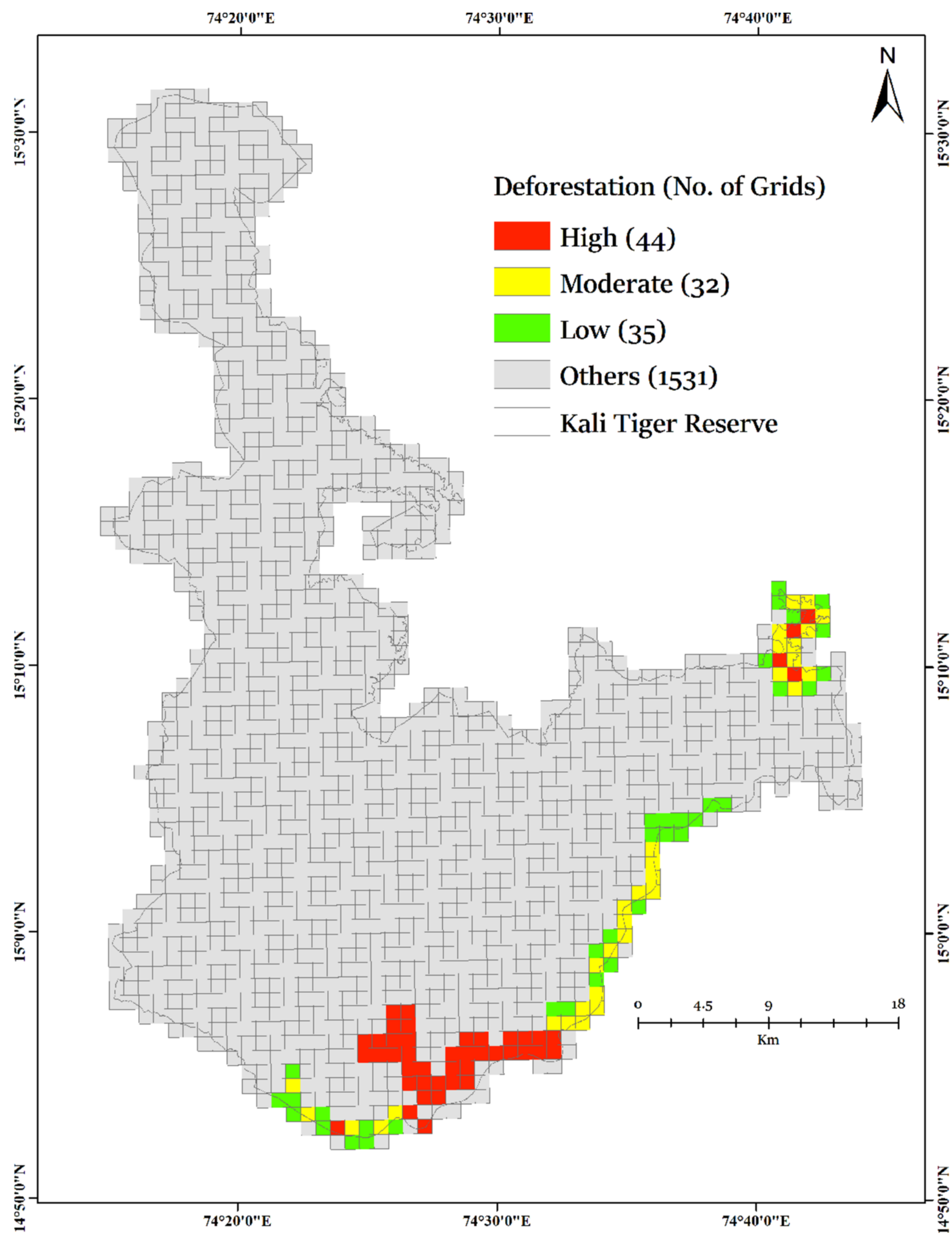

Fig. 4 Grid-based distribution of deforestation risk categories in the KTR. 'Others' denotes grids not affected by deforestation at the defined thresholds

fire ignitions, resulting in the formation of prominent fire hotspots. During the study period (2012–2023), a total of 2,574 fire events were recorded within the Kali Tiger Reserve. Hotspot analysis revealed that fire occurrences were predominantly concentrated in the eastern part of the reserve, with 16.6% of the 1 km² grid cells identified as fire-prone areas (Fig. 7).

Mono-plantations (2023)

A total of 147 grid cells (8.95%) contained mono-plantations, which were predominantly concentrated in the eastern part of the Kali Tiger Reserve. The major plantation species were areca nut, teak, and eucalyptus. Areca nut plantations, which have expanded since the 1990s, were primarily distributed within the low-risk category. The total area under mono-plantations was 2,074.53 ha, of which approximately 83% comprised teak and eucalyptus plantations. Based on the predefined area thresholds, 1,400.38 ha was classified as High (32 grids), 325.69 ha as Moderate (22 grids), and 348.45 ha as Low (93 grids) (Fig. 8).

Spatial Tracking of Multi-threat Hotspots (MTH)

The integrated multi-threat assessment evaluated four major forest threats deforestation, landscape fragmentation,

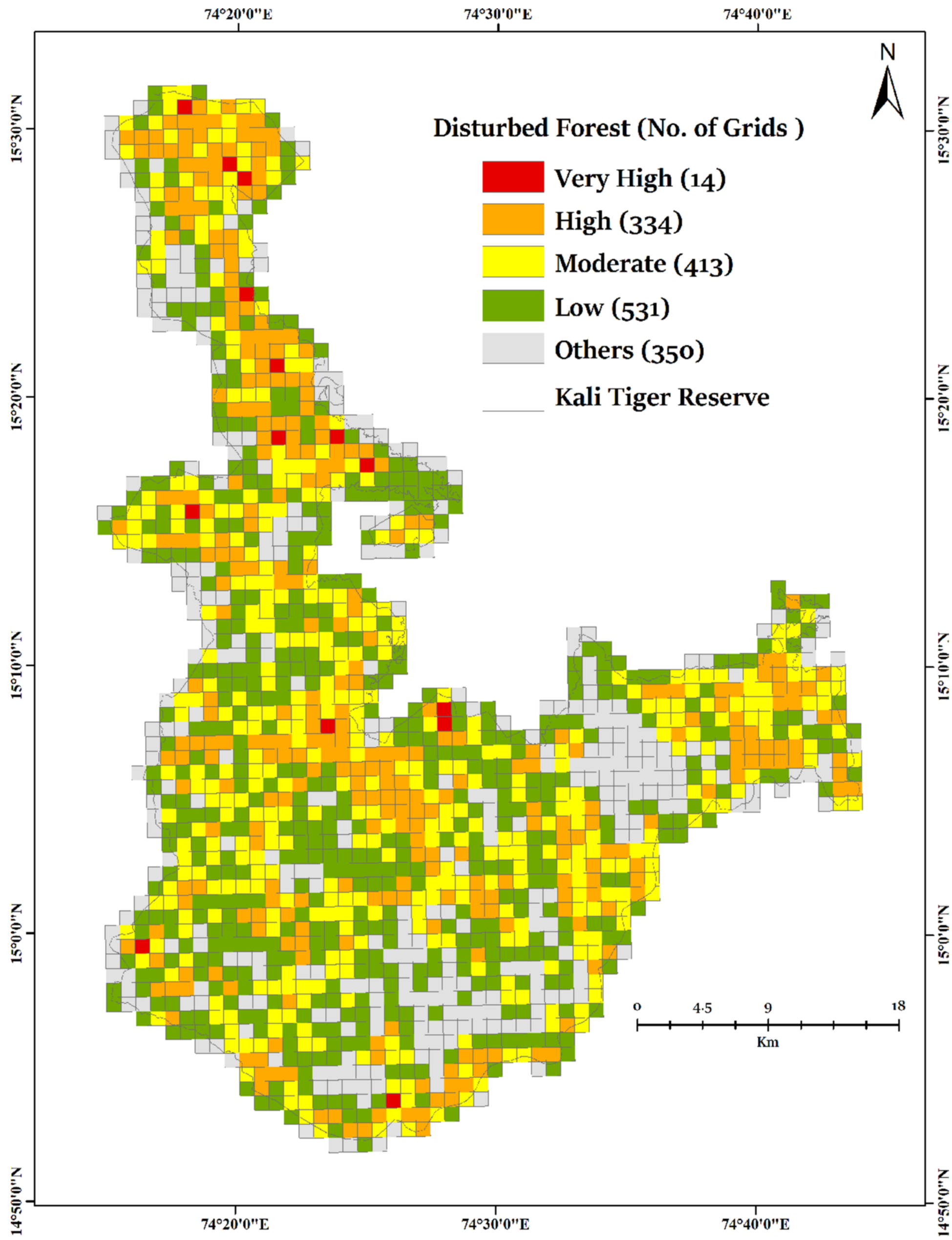

Fig. 5 Grid-based distribution of disturbed areas in the KTR, derived from landscape fragmentation analysis. 'Others' denotes grids that did not exhibit fragmentation at the defined threshold levels

mono-plantations, and forest fires across the Kali Tiger Reserve (KTR). The cumulative threat analysis identified 63 grid cells (3.8%) as Very High Risk and 200 grid cells (12.18%) as High Risk, indicating areas where multiple threats spatially overlap. In addition, 811 grid cells (49.3%) were classified as Moderate Risk, while the remaining 33.4% were categorized as Low Risk (Fig. 9).

The spatial distribution of multi-threat hotspots revealed that the southern and eastern regions of the reserve are subjected to the greatest cumulative threat intensity. These areas represent priority zones for conservation and management interventions, where integrated measures to mitigate multiple concurrent threats should be prioritized.

The LULC classification accuracy was assessed using stratified random sampling points across the landscape, resulting in a user accuracy of 0.96 and a Kappa coefficient of 0.92. Details of the accuracy assessment and major LULC changes are provided in Supplementary Tables S1 and S2, respectively.

Discussion

This study evaluated the multiple threats in the study area over the past four and a half decades. The multi-source and multi-temporal data coupled with ancillary datasets have

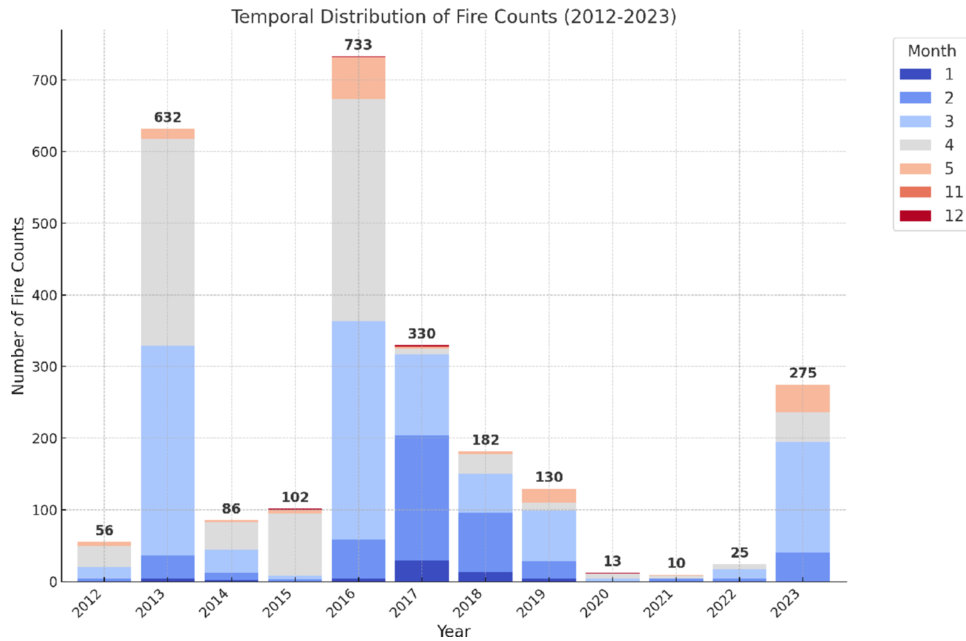

Fig. 6 Temporal distribution of forest fire occurrences in the Kali Tiger Reserve (KTR) during 2012–2023

proven to be potential in detecting multi-threat hotspots. There has been a notable research gap in this key biodiversity area. Earlier studies have focused on the aspects of biodiversity, habitat loss, and fragmentation (Ramachandra et al., 2017; Tripathy et al., 2024; Kulkarni & Hegde, 2015). Assessing multiple and coinciding ecological threats using a location-based approach within PA, and understanding their cumulative impacts, is understudied (Wani et al., 2024). To develop robust management strategies, using multi-source and multi-temporal data, mapping various periods, and focusing on multiple threats rather than individual issues is essential (Karimi et al., 2023; Wani et al., 2022). Therefore, it is imperative to comprehend multiple threats in a spatial framework as a prerequisite for more nuanced management.

Multiple threats included deforestation, fragmentation, invasive alien plant species (IAPS), and forest fires using spatial a 5 km × 5 km grid for Odisha and Telangana (Reddy et al., 2014 and Sudhakar et al., 2015). However, using a finer grid allows for precise identification of localized changes, aligns well with remote sensing data, and serves as a practical unit of analysis for regional-scale assessments. A study by Saranya & Reddy (2016) analysed long-term changes in forest cover and land use in the Similipal Biosphere Reserve, Odisha, using a one km^2 grid-based approach between 1930 and 2012. These studies highlight the need to conserve areas with overlapping threats by offering detailed spatial evidence of combined ecological disturbances, which aligns with global frameworks to guide targeted conservation efforts in endangered regions. To achieve this, continuous monitoring is essential for understanding recent changes and developing holistic conservation strategies for ecosystems under complex and interconnected pressures.

A one km^2 grid-based assessment also provides an opportunity to integrate datasets such as the National Initiative on Climate and Environmental Studies (NICES), where compatible spatial resolutions can improve monitoring efficiency and reduce analytical uncertainties. Such integration can enhance understanding of how habitat conditions within individual grid cells influence local microclimatic variations and ecosystem responses.

The landscape of KTR has been fragmented in the last five decades, mainly due to infrastructural development and anthropogenic activities. The present study examines and quantifies fragmentation within a truly natural landscape, separating human-modified areas, contrasting with prior research focused on forest fragmentation (Bogaert et al., 2011). Such an approach enables robust identification of disturbed areas within the habitat. It is evident through previous studies that these disturbed areas can alter the microclimate and degrade the habitat (Paul & Banerjee, 2021; Reddy et al., 2014; Sudhakar et al., 2015). In fragmented surfaces, the sunlight directly reaches the ground, resulting in increased land surface temperature and altering the microclimate (Swarada et al., 2024b). Fragmentation induced microclimatic changes impact animal behaviour and ecosystems (Tigreros et al., 2023). These changes can endanger the survival of rare and sensitive species within the PA, which rely on stable conditions. IAPS often establish in these areas due to their phenotypic plasticity (Swarada et al., 2024b; Tiwari et al., 2022; Rindyastuti et al., 2021; Rai & Singh, 2020).

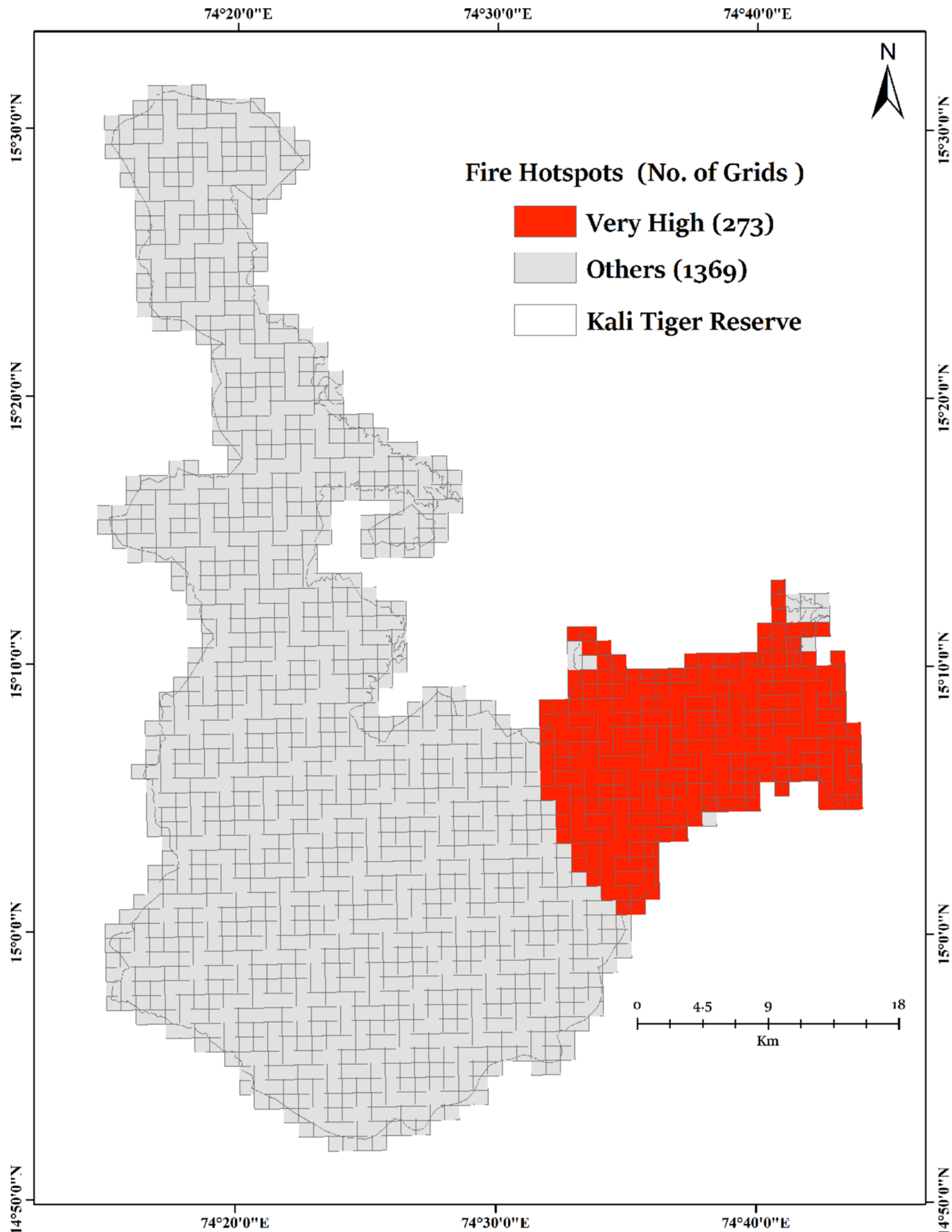

Fig. 7 Grid-based distribution of forest fire hotspots in the Kali Tiger Reserve (KTR). Fire-prone grids were identified using the Getis–Ord Gi* hotspot analysis. 'Others' denotes grids that did not exhibit statistically significant fire hotspot activity or did not meet the defined hotspot threshold

In disturbed landscapes, IAPS like *Lantana camara* and *Chromolaena odorata* survive in well-lit, open-edge areas as they can thrive in disturbed or transitional environments (Tiwari et al., 2022; Rindyastuti et al., 2021; Rai & Singh, 2020). Native species adapted to the stable conditions of undisturbed interiors find these altered environments unsuitable (Meyer et al., 2021; Pasha & Reddy, 2024). The establishment of *Chromolaena odorata* in unrestored canopy gaps of KTR is evident through a study which is an alarming sign and needs attention for restoration (Swarada et al., 2024b). Literature indicates that fragmentation reduces biodiversity and disrupts ecological functions, further exacerbating the challenges posed by climate change. These fragmented areas, particularly within a PA, are also susceptible to forest fires due to increased human interference (Chaudhary et al., 2022).

The literature indicates that, in India, forest fires are predominantly anthropogenic in origin, with surface fires being the most common type. Tropical dry deciduous forests are particularly vulnerable to these fires, resulting in significant ecosystem-level impacts (Srivastava & Garg, 2013; Joseph et al., 2009; Negi, 1986; Roy, 2003). Since KTR has a dominance of deciduous forests with events of recurrent forest fires, it is a prerequisite to execute effective monitoring, mitigation, and recovery of impacted areas in the identified hotspots. The eastern region of the TR is susceptible to fires,

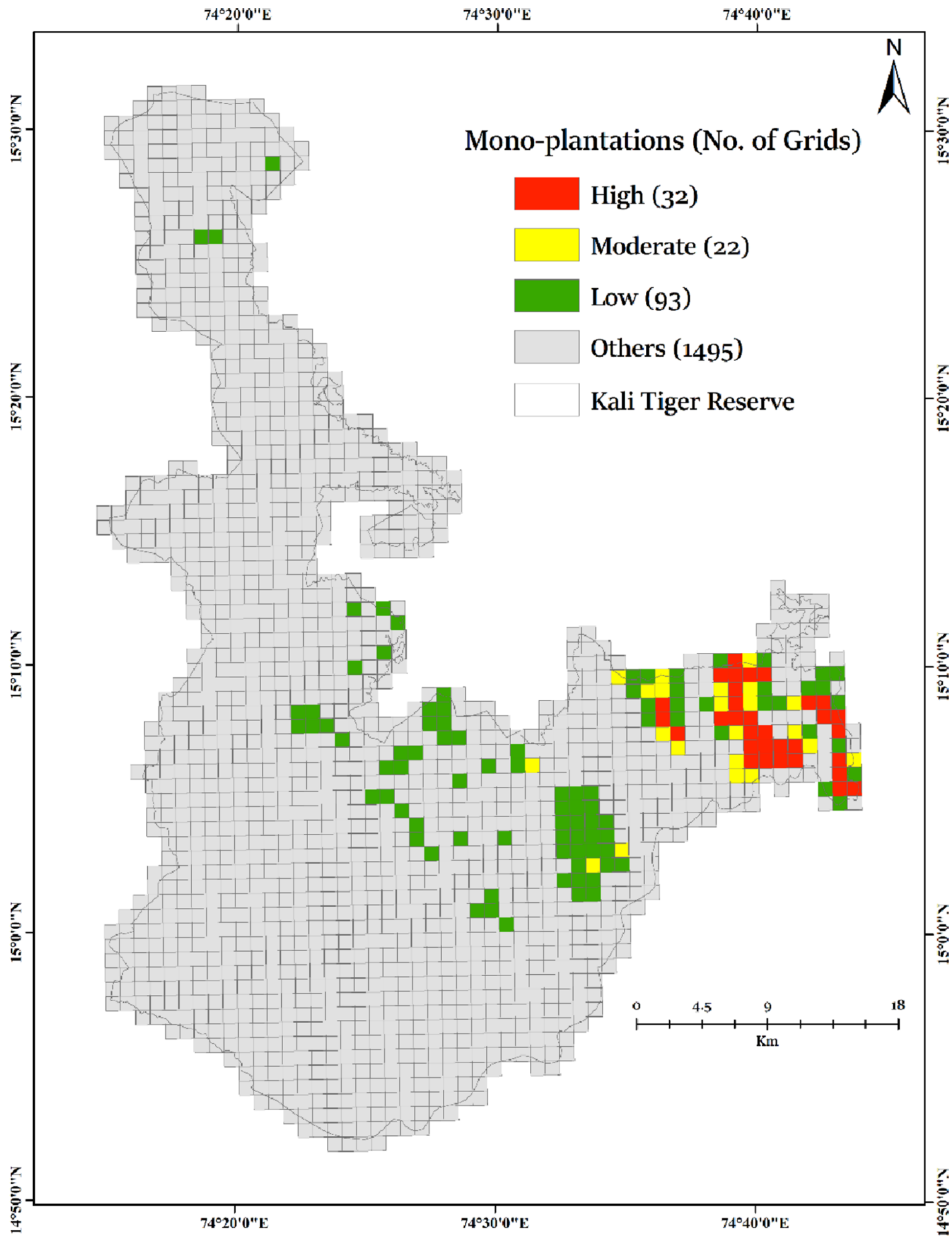

Fig. 8 Grid-based distribution of mono-plantation intensity classes in the KTR in 2023. 'Others' represents grids without mono-plantations or those below the defined area thresholds

compounded by the prevalence of teak mono-plantations, which exacerbate the vulnerability, necessitating urgent attention.

The plausible reasons for deforestation and increased fragmentation can be anthropogenic or natural. From 2002 to 2023, Uttara Kannada lost 5.44 kha of tree cover, equivalent to a 0.75% decrease in tree cover since 2000, and 2.96 Mt of CO_2 emissions (Hansen et al., 2013). According to the India State of Forest Report (ISFR) 2023, the WG lost 58.22 km^2 of forest cover over the past decade, with Karnataka's Shivamogga and Belagavi districts experiencing severe degradation, losing 74.5 km^2 and 24.9 km^2, respectively (ISFR, 2023). This results in fragmentation of land, reducing biodiversity, ecosystem functionality, and altering the microclimate (Wilson et al., 2016). The current study enhances the assessment of tree loss or deforestation by integrating advancements from previous research. For instance, in quantifying tree loss or deforestation, the definition of forest has been adapted from Reddy et al., 2016, thereby addressing the discrepancies discussed in the study by Pasha & Dadhwal, 2024. The TR has experienced landslides resulting in the loss of pristine forest cover due to catastrophic rainfall events. A detailed study by (Swarada et al., 2024b) has identified and mapped the landslides in and around KTR, investigating the dynamics of pre- and post-LS. The study evidences the emergence of IAPS *Chromolaena*

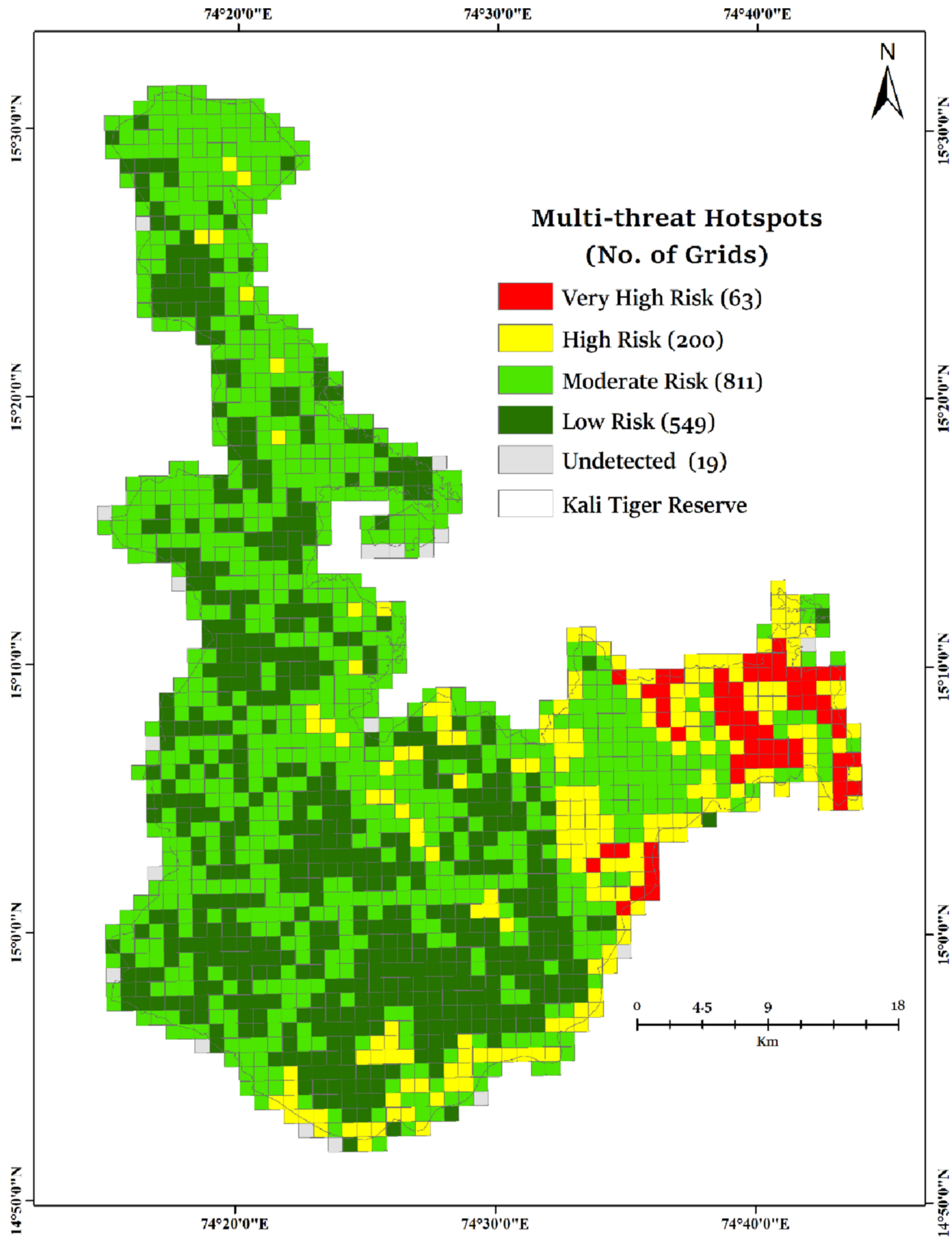

Fig. 9 Spatial distribution of multi-threat hotspot grids across the study area

odorata and the increase in land surface temperature (LST) in the impacted areas (Swarada et al., 2024b). The spread of *Chromolaena odorata*, which is listed as one of the worst 100 global IAPS (https://www.iucngisd.org) indicates the threat to native biodiversity and increased LST alters micro-climate, leading to unsuitable conditions for native species. If these areas remain unrestored, they can serve as potential sites for future landslides (Geertsema et al., 2009). Hence, the present study has categorized these locations under the high-risk category.

The eastern portion of the PA has teak and eucalyptus mono-plantations which were established here during the colonial period (Rathod et al., 2024). Teak mono-plantations are characterised by low biodiversity, and lack of regeneration, soil degradation and contribute to an increase in LST (Swarada et al., 2024a; Ramachandra et al., 2018; Mahmud et al., 2018). These mono-plantations are unsuitable habitats for wildlife and native vegetation needs to be restored by preparing ecologically sound plans (MoEFCC, 2023). A recent study shows that even after 100 years, these plantations have not naturalised and are hindering the forest integrity (Swarada et al., 2024a). The current study witnessed that the agricultural land in KTR has transitioned into arecanut plantations. Karnataka is the largest producer of arecanut with 68% of national production; owing to its economic importance, this increase is observed.

Although previous studies on KTR have focused on specific threats, this study provides a more comprehensive analysis by examining multiple ecological threats. The systematic grid-based approach identifies multiple-threat hotspots that act as a proxy to concentrate on areas for targeted conservation. This integrated framework offers valuable insights for adaptive management, ensuring the long-term ecological stability of both KTR and the larger Western Ghats landscape.

Conclusion

This study underscores the importance of multi-threat hotspots, using temporal satellite images and field data for targeted management strategies in KTR. Despite its strict conservation measures, the KTR faces multiple ecological challenges mainly due to human and climate factors. This approach has sufficient merit to provide insights into various forest disturbance regimes. The identification of multi-threat hotspots facilitates a clear roadmap for sustainable natural resource management. This study advocates for the restoration of grids with multiple threats. This integrated approach aligns with global biodiversity frameworks and provides actionable strategies for sustaining ecological health and resilience in KTR. Expanding this methodology to other PAs can contribute significantly to addressing multiple ecological challenges. Future studies should include other proxies such as biological invasion and historical burnt area.

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Author Contributions The study was conceived and planned by Shaik Vazeed Pasha (SVP), Swarada Badhe (SB), TN Manohara (TNM), and Vinay Kumar Dadhwal (VKD). The task of compiling and analysing the data was undertaken by SVP and SB. TNM and SB were responsible for collecting and understanding field data. The data processing workflow was established by SVP and SB. SB, SVP, TNM, and VKD collaborated in creating the figures and tables, analysing the data, writing the manuscript, and revising it. The overall guidance and data curation were accomplished by VKD.

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Data Availability The datasets utilised in this study, which include multi-spectral and multi-temporal satellite imagery (Landsat series, Sentinel-2 A), MODIS and VIIRS fire data, and ancillary datasets such as Survey of India toposheets and Open Building footprints, are sourced from publicly available repositories. Historical Landsat data were obtained from the United States Geological Survey (USGS) Earth Explorer platform, while Sentinel-2 A images were retrieved from the Copernicus Open Access Hub. Fire location data were sourced from NASA's Fire Information for Resource Management System (FIRMS). All geospatial analyses and derived datasets used in the study are available upon reasonable request from the corresponding official sources. These datasets are accessible through their respective official platforms, ensuring reproducibility and transparency.

Declarations

Conflict of Interest The authors declare no competing interests.

Ethical Approval All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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