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Conservation Prioritization of Ecologically Sensitive Regions with the Insights of Forest Dynamics at Disaggregated Levels

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ABSTRACT

The comprehensive knowledge of the ecological fragility of a region is quintessential for evolving strategies for the conservation of the area. This entails identifying factors responsible for ecological sensitiveness, including landscape dynamics, future transitions to mitigate the problems of haphazard and uncontrolled development approaches. The escalating anthropogenic pressures leading to over-exploitation of natural resources and unabated greenhouse gas emissions have contributed to global warming leading to changes in the climate and depletion of natural resources. The forest dynamics for the Mysore district were assessed using temporal remote sensing data and the field data and predicted future scenarios of transformation, which helps in evolving appropriate management strategies. Ecological sensitive regions at decentralized levels (grids of 5' × 5' or 9 km× 9 km) have been identified in Mysore district, Karnataka State, India, through a composite metric based on bio, geo, hydro, climatic, and ecological factors with the social aspects. This information was compiled from the field through a natural environment survey at representative grids and an extensive literature review at the district level.

Forest dynamics were assessed using a supervised classifier based on the Gaussian maximum likelihood classifier using temporal remote sensing (1989 to 2019) Landsat data. The study showed an increase in agricultural lands in Mysore from 64.4% (1989) to 68.6% (2019). The forest range of the Mysore was dominated by the dry deciduous and moist deciduous forest in the Bandipuara and Nagar holé reserved forest. Anthropogenic activities such as urbanization, eco-tourism, etc., have resulted in the decline of forest cover from 19.39% (1989) to 13.08% in 2019. The fragmentation analysis showed a decline of contiguous interior forest from 50.66% to 42.41% (1989 to 2019) in Mysore. Likely land-use scenario reveals an increase in built-up from 3.03 to 4.31% (2029) for the loss of forest area from 15.51% (2019) to 15.42% (2029). Computation of spatial matrices proves the higher urbanization and loss of forest cover in the outskirts of city centers. Integrating geo-climatic, social, hydrological, and ecological parameters for each grid helped delineate ESR based on the aggregate values. Fourteen grids (17.07%) in Mysore fall in ESR 1, indicating the highest sensitivity. 21.95% in ESR2 (higher sensitivity), 58.5% constitute ESR 3 (high sensitivity) and the rest is 2.43% in ESR 4 (moderate sensitivity). The region-specific sustainable development path with cluster approaches would enhance job opportunities and optimize local resource use at each panchayat (grid) level with negligible effects on ecosystem health.

Key words: Biodiversity, Conservation, Cluster-based development, Ecological fragility, Endemic Species, Forest dynamics

INTRODUCTION

Globally, forest ecosystems now occupy 1.7 million ha, which has reduced from 2.5 million ha (1999-2000) at the rate of 2% per annum (FAO, 2010). Forests play a pivotal role in mitigating global climate warming by sequestering carbon (C) from the atmosphere and storing it C into various components. Further, they provide an array of goods and ecosystem services and protection from natural hazards and regulate ecological and hydrologic processes for the well-being of society (Costanza et al. 1997, Pramova et al. 2012). Forest ecosystems offer critical, diverse services to humankind, provide a primary habitat for a wide range of species, sustain biodiversity, environmental processes, and reduce the risks of natural disasters such as droughts, floods, and landslides. Forest transitions encompass changes in stand structure, species composition, and interactions with disturbance and environment over various spatial and temporal scales. Establishing a uniform assessment system by considering relative factors that reflect distinct ecological characteristics would aid in implementing conservation measures (Chen et al. 2018).

Landscape refers to an ecological space with a mosaic of heterogeneous elements, and structure (composition and configuration) determines ecosystem functions and hence sustenance of natural resources. Alteration in the landscape structure due to the sustained anthropogenic pressure has induced fragmentation, which has led to a loss of natural habitat, connectivity, and biodiversity. Landscape dynamics driven by either natural phenomenon or caused by humans, would with changes occurring in the physical space are. Landscape dynamics operating along with a broad range of temporal and spatial scales in the physical, biological, and cognitive assets change the stability, persistence, resistance, resilience, and recovery properties. Landscape dynamics are reflected through the changes in land use land cover. Understanding landscape dynamics are crucial for prudent management of natural resources (land, water, etc.) and conservation. However, unplanned developmental activities have affected the sustenance of natural resources evident from the barren hilltops, conversion of perennial streams to the seasonal streams threatening water security, loss of topsoil threatening food security, etc.

Land cover refers to the earth's physical surface that depends on the existing natural resources and natural processes that are dynamic. Land use (LU) indicates the use of land for anthropogenic purposes through alterations in land cover (Ramachandra and Bharath 2018). LULC changes alter the landscape structure either due to natural or anthropogenically induced over a period. Drivers of LULC changes are categorized into (i) proximate drivers having a direct impact on the landscape with alterations in its composition such as agriculture expansion, infrastructure, settlements, etc., and (ii) underlying driver influencing indirectly through a set of existing drivers such as population dynamics, agricultural policies, markets, etc., (Plieninger et al. 2016).

Changes in LULC will have a distinguishable impact on the landscape at a local scale with alterations in the ecosystem processes. This will lead to biodiversity loss, alterations in the hydrologic regime, loss of carbon sequestration capability, enhanced emissions of greenhouse gases (GHG), global warming with changes in the climate (Lambin et al. 2003, Vinay et al. 2013, Hersperger et al. 2010, Ramachandra et al. 2018, 2020). Hence, mapping and monitoring the LULC changes help resource management through sustainable planning activities.

Large-scale LULC changes lead to the fragmentation of forest ecosystems by breaking the contiguity of forests into fragments with modifications in the structure and composition of forests (Ramachandra et al. 2016). Alterations in the structure of an ecosystem affect the food chain with the loss of habitat, decline in the carbon sequestration potential (Puhlick et al. 2017), and enhance carbon emissions, which necessitates a comprehensive understanding of the landscape structure for effective management of natural resources. The sustained overexploitation of biological resources involving landscape transformations leads to the degradation of the ecosystem. Fragmentation has been a greater threat to the forest ecosystems (decreased natural patch size, increased patch isolation, and increased edge area).

It affects the natural resilience and connectivity among forest habitats, posing challenges for adapting to climate changes. The consequences of expanding non-forest land uses are habitat degradation, hydrological alterations, higher soil erosion, increases in invasive plants, sturdy pests, pathogens, etc. (Wilson et al. 2016). Understanding the importance of the intact ecosystems would provide insights into the conservation-based decision-making towards the sustenance of natural resources to meet the present and future needs (Ramachandra et al. 2016).

The sustainable development agenda across countries in the globe to reduce the anthropogenic impacts proposes a radical shift in the development paradigm with strict conservation measures (Angelsen et al. 2014). A comprehensive understanding of the functioning of social-ecological systems and their interactions is required to mitigate abrupt LULC changes in forest landscapes, which helps in framing effective policies for the sustainable management of natural resources. Geoinformatics with Geographical Information System (GIS) and availability of spatial data at regular intervals since the 1970's obtained through space-borne sensors

(Remote Sensing (RS) data) have helped understand LULC changes with drivers of changes. Availability of the multiresolution (spectral, spatial, and temporal resolutions) remote sensing data have enabled to assess the landscape dynamics aiding planners, land managers to efficiently evaluate landscape changes at local and regional scales (Lambin et al. 2003, Wu et al. 2006, Ramachandra et al. 2014). Modeling and visualization of likely land-use changes help in the identification of growth poles for formulating sustainable policies toward the prudent utilization of natural resources that provides an opportunity to mitigate impacts (Bharath et al. 2021). The quantification of LULC changes and visualization of likely changes has been carried out through various statistical approaches, such as linear, logistic regression models, multivariate analyses, empirical and non-statistical techniques across the globe (Hietel et al. 2007, Wheeler and Calder 2007, Hersperger et al. 2010, Bieling et al. 2013, Bharath et al. 2014, 2021, Ramachandra et al. 2017, Egli et al. 2018, Bharath and Ramachandra 2021). The modeling and visualization of LULC assist in identifying ecologically fragile regions, which helps in framing policies and regulating anthropogenic activities through the active participation of all stakeholders (Ramachandra et al. 2018).

The ecological sensitivity or fragility refers to unique ecosystems with the predominant natural ecological interactions affected by anthropogenic activities due to mismanagement (Nilsson and Grelsson 1995). A congregation of unique landscape elements or regions that is vital for sustaining ecological processes is often known as Ecological Sensitive regions (ESRs) or Ecologically Fragile regions (EFRs). Mismanagement of ESR/EFR leads to water scarcity, loss of biological diversity, recurring instances of floods and droughts, loss of crop productivity, the decline of goods and services with the loss of livelihood. This necessitates mapping ecologically sensitive or fragile or susceptible regions (ESRs) by integrating bio-geo-climatic-hydrologic-ecologic parameters with the social aspects and assigning weights (based on the extent and condition of factors). ESR provides a comprehensive understanding as a reliable decision support system for conservation (Ramachandra et al. 2018). The final ESR map would guide the biodiversity management committee (BMC) in the decision-making at decentralized levels (panchayath levels) as per the goals of the Biodiversity Act, 2002, GoI towards the conservation of ecologically fragile regions. The current study identifies ecologically fragile regions at decentralized levels in Mysore district Karnataka using temporal RS data and the collateral data (bio-geo-climatic, hydrologic regime, ecological and social aspects).

MATERIAL AND METHODS

Study Area

Mysore district covers an area of 6854sq.km and extend between 11°45' to 12°40' N (Latitude) 75°57' to 77°15' E (Longitude), is located in the central Western Ghats (Fig. 1) and has eight taluks, namely Mysore, Tirumakudalu Narasipura, Nanjangud, Heggadadevanakote, Hunsur, Piriyapatna, and Krishnarajanagar. The region lies on the Deccan plateau, east of the hilly Malenadu region, which includes the eastern foothills of the Western Ghats range, and the average annual rainfall is 776.7 mm. The population in 2001 was 26,41,027 persons, which increased to 30,01,127 persons in 2011 with a growth rate of 13.63% (Census 2011). The population density of the district is 476 persons/km^2.

Major crops cultivated in Mysore are paddy (*Oryza sativa*), jowar (*Sorghum* sp.), bajra (*Pennisetum glaucum*), maize (*Zea mays*), ragi (*Eleusine coracana*), wheat (*Triticum aestivum*), tur dal (*Cajanus cajan*), horse gram (*Macrotyloma uniflorum*), black gram (*Vigna mungo*), green gram (*Vigna radiata*), avare (*Lablab purpureus*), cowpea (*Vigna unguiculata*). Sugar cane (*Saccharum officinarum* L.), cotton (*Gossypium herbaceum* L), and coconut (*Cocos nucifera*) are the main horticulture products. Various soil types in the district are red sandy soils, red loamy soils, and deep black soils. The entire district is covered by red sandy soil except for a small part of T. Narasipur taluk. North-eastern, South-western parts of T. Narasipur taluk comprised of red loamy soil and Deep Black soil, respectively.

There are four distinct seasons such as (i) four wet months of June, July, August, and September with strong winds, high humidity; (ii) two damp and warm months of October and November; (iii) three

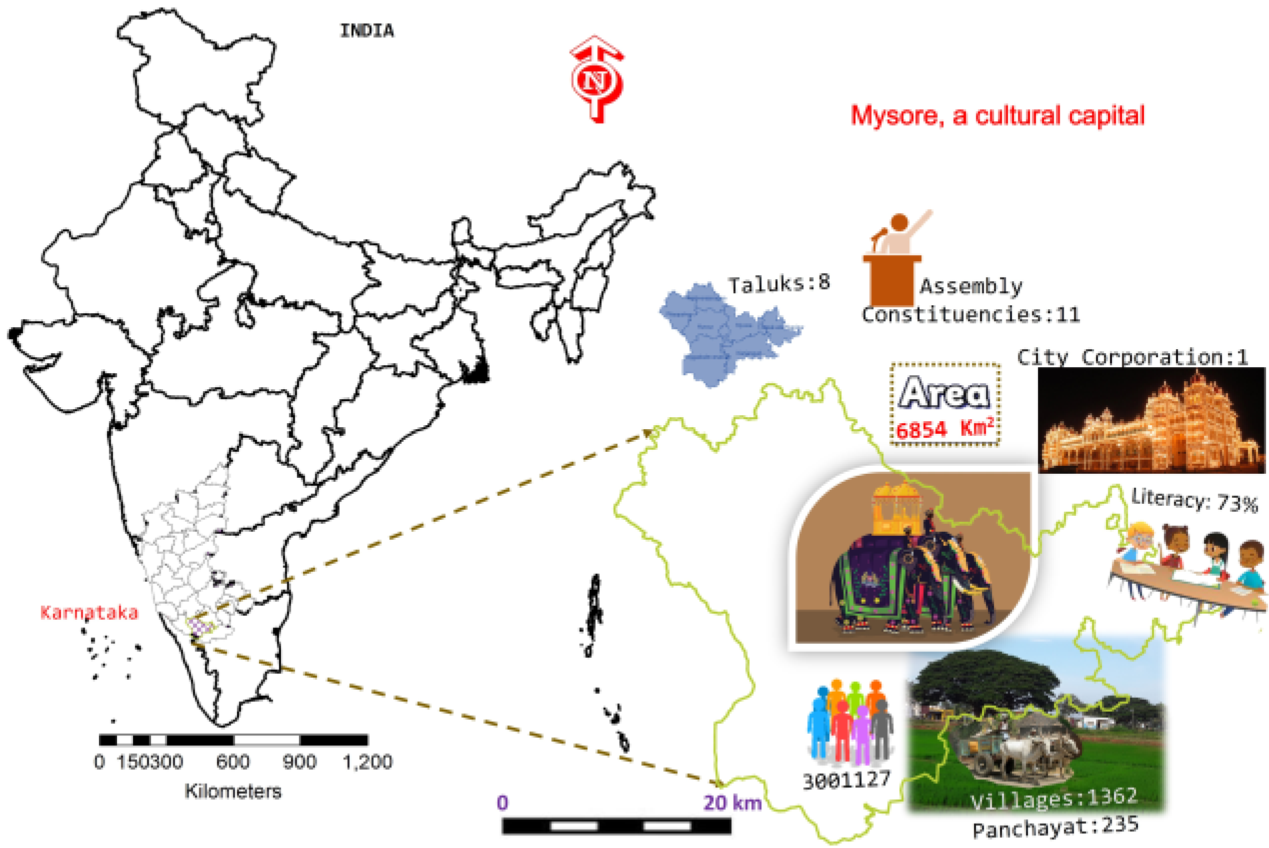


Figure 1. Study area - Mysore district, Karnataka State, India

cool months of December, January and February; (iv) three hot months of March, April and May. The Cauvery River drains the district along with Kabini and Lakshmanathirtha tributaries. Irrigation by canals is a characteristic feature of the district. The climatic condition of the district is moderate throughout the year. The district is the second richest district in forest wealth next to Uttara Kannada.

The district contributes [1] 138 billion to GDP and contributes 4.5% to state GSDP. The district is known for its traditional industrial activities such as silk reeling, handloom, and silk weaving and crafts like inlaid works. Rearing silkworms is one of the major cottage industries of the district, and thus stands first in sericulture. Mysuru district is one of the state's prosperous districts, considering its progress in the development and utilization of irrigational facilities, exploitation of forest wealth, and sericulture potentiality. There are about 30,574 small-scale and medium-scale industries and about 745 large-scale industries. Groundwater contributes to about eighty percent of the drinking water, while about 20% of the population depends on the rivers like Cauvery, Kabini, and many other lakes.

Forest ecosystems in the district include open-canopied tropical dry deciduous forests, characterized by the trees *Acacia*, *Albizia* and *Hardwickia*, *Canthium parriflorum*, *Cassia auriculata*, *Dodonaea viscosa*, *Erythroxylum monogynum*, *Pterolobium hexapetalum* and *Euphorbia antiquorum* (Rao and Razi 1981). Flora in the district is rich and diverse, with 1601 flowering plants belonging to 170 families and 778 genera (Rao and Razi 1981, Ganeshaiah et al. 2002). As per Karnataka Forest Department, Mysore circle (KFD 2020), there are 326 bird species, comprising 182 Residents, 87 Regular winter visitors, 13 Rare winter migrants, 30 Vagrants, and 14 birds overshooting their habitat from surrounding Eastern & Western Ghat and Shores. This accounts for 26% of 1225 species of Indian avifaunal diversity (Islam and Rahmani 2005). Fauna documented during the field investigations and reported *(KFD, 2020)* in this region are Leopard (*Panthera pardus)*, Jungle cat (*Felis chaus)*, Rusty spotted cat (*Felis rubiginosa),* Indian Fox (*Vulpes bengalensis*), Small Indian Civet (*Viverricula indica)*, Common palm civet (*Paradoxurus hermophroditus)*, Common mongoose

(*Herpestes edwardsi)*, Black buck (*Antilope vervicarpa)*, Wild pig (*Sus scrofa)*, Porcupine (*Hystrix indica)*, Pangolin (*Manis crassicaudata),* Black-naped hare (*Lepus nigricollis*and), and Bonnet macaque (*Macaca radiata).*

Methods

Identifying ecologically sensitive regions has been carried out in three phases as outlined in Figure 2by adopting the grid-based approach of the National Environmental Survey [NES] of MoEFCC, GoI. The work involved (i) assessment of landscape dynamics using temporal RS data in phase 1, (ii) modeling and visualization of landscape dynamics in phase 2, and (iii) in phase 3, collating diverse information for prioritization of the ecologically sensitive regions at decentralized levels in the district.

(i) Quantifying landscape dynamics

The temporal RS data from 1989 to 2019 were downloaded from public domain archives of Earth Observatories (https://earthexplorer.usgs.gov/). Training data and ground control points were compiled from the field across the representative ecosystems of the district through pre-calibrated GPS (Global Positioning System) for geo-registration and supervised classification of RS data. This was supplemented with the collateral data collected from the secondary sources, which include French institute Puducherry vegetation maps (Pascal1993), the Survey of India topographic maps of 1:50,000, Biodiversity portal (http://indiabiodiversity.org/), and Virtual earth data such as Google Earth (http://earth.google.com), Bhuvan (http://bhuvan.nrsc.gov.in). Data Pre-processing was implemented through geo-registration (Geo-referencing or assigning coordinates with projection) and Radiometric correction (calibration and correction of pixel values). Land cover analyses were done to compute the spatial extent of areas under vegetation and non-vegetation through the computation of vegetation indices (given by equation 1) using GRASS 7.6.1. The temporal land cover analysis is carried out for the study area for 1989, 1999, 2009, and 2019.

$$NDVI = {(NIR - R)}/{(NIR + R)}. \quad \textbf{(1)}$$

The RS data classification for quantifying LU categories involved (i) the creation of False Color Composite, which aided in identifying heterogeneous regions in a scene, (ii) selection of training sites or digitizing sample polygons corresponding to heterogeneous regions, covering at least 15% of the study region and are uniformly distributed, (iii) supervised classification of RS data based on Gaussian maximum likelihood algorithm and (iv) accuracy assessment using training data through computation of kappa statistics and confusion matrix (error matrix). The field investigation and virtual data portals such as Google Earth (earth.google.com) and Bhuvan (bhuvan.nrsc.gov.in) helped in the collection of attribute information of these sample polygons for classifying RS data (supervised classification approach).

A supervised classification technique based on the Gaussian Maximum likelihood classifier considering training data is one of the best and most commonly used classification approach (Vinay et al. 2013, Bharath et al. 2014, Ramachandra et al. 2016, 2018). The supervised classification scheme-based Gaussian maximum likelihood classifier (GMLC) is adopted for the classification under six different LU categories using GRASS GIS (Geographical Analysis Support System). GRASS is a free and open-source geospatial software with robust functionalities for processing vector and raster data available at (http://wgbis.ces.iisc.ernet.in/grass/). The training data (60%) collected was used for classification, while the balance is used for accuracy assessment to validate the classification. The test samples are then used to create an error matrix (also referred to as confusion matrix), kappa (ê) statistics, and overall accuracy with the producer and user accuracies to assess the classification accuracies (Lillesand et al. 2014). The classified information is validated through the computation of the error matrix considering an adequate number of sample points representing different LU categories for a one-to-one comparison of the categories. Based on the confusion matrix (errors of commission and omission), accuracy estimation is done in terms of producer, user, and overall accuracies. The LU information is used as input for fragmentation analysis.

Fragmentation of forests is estimated through the standard protocol (Riitters et al. 2002, Ramachandra et al., 2016) by computing P_f(the ratio of the number

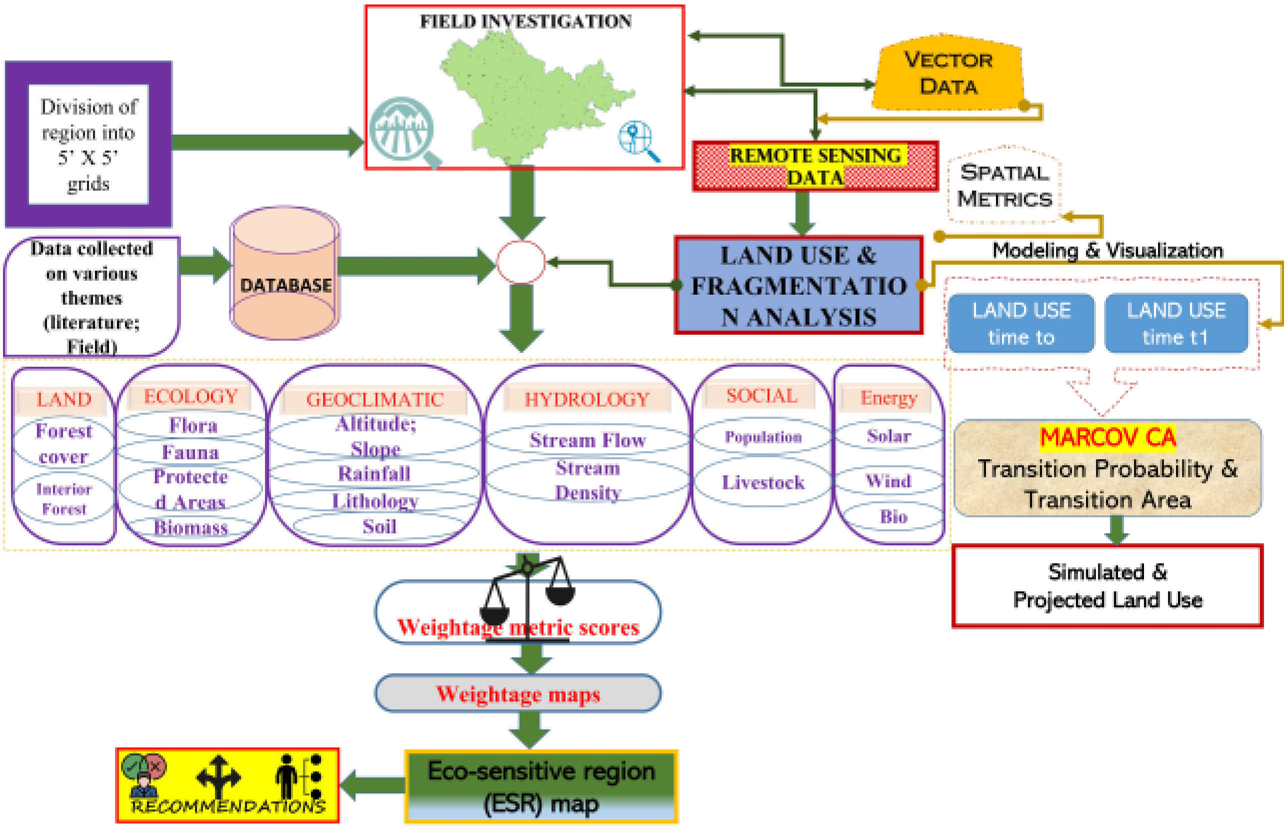


Figure 2. The method used for LU analyses and identification of ESR

of pixels that are forested to the total number of non-water pixels in the window) and P_{ff} (the proportion of all adjacent (in cardinal directions only) pixel pairs that include at least one forest pixel, for which both pixels are forested) as given in equations 1 and 2 (Riitters et al. 2002, Kuèas et al. 2011, Ramachandra et al. 2016).

$$P_f = \frac{\text{Proportion of number of forest pixels}}{\text{Total number of non-Water pixels in window}} \quad (2)$$

$$P_{ff} = \frac{\text{Proportion of number of forest pixel pairs}}{\text{Total number of adjacent pairs of at least one forest pixel}} \quad (3)$$

P_{ff} estimates the conditional probability that given a pixel of the forest, its neighbor is also forest-based, the proportion of all adjacent (cardinal directions only) is also a pixel pair. P_f and P_{ff} were computed through a moving window of 5×5 pixels in order to maintain a fair representation of the proportion (P_f) of pixels and to maintain the interior forest at an appropriate level, given that the results of the model are scale-dependent and threshold dependent (Ritters et al. 2000, 2002, Wickham et al. 2007, Kuèas et al. 2011). Details of the spatial extent of forest fragmentation were mapped based on the indices P_f and P_{ff} with classification criteria as presented in Table 1.

(ii) Modeling and visualization of landscape dynamics

The temporal LU analysis provided spatial dynamics, which is provided as an input to the Markovian process. The markovian process is random, defines the suitability of state as a weighted linear sum of a series affecting factors, normalized to values in the range of 0–1. Thus, neighborhood influence area is calculated as a cumulative effect of each transitional potential and its interaction with its neighbors. The transition rules were determined by various demands of the LU categories, population growth, etc. Two temporal LU spatial maps were used to account for the stable and transformed LU categories which satisfy non-transition properties such as urban category to water or vice versa. The transition probability map and area matrix is obtained based on a probability distribution over the next state of the current cell that is assumed to only depend on the current state (Equations 3 and 4). A transition probabilities matrix determines the likelihood of a

Table 1. Fragmentation components and their description

Fragmentation component	Description	Computation
Interior	Forest pixels are far away from the forest-non forest boundary. Interior forested areas are surrounded by thicker forested areas.	($P_f = 1$). All pixels surrounding the center pixel are forest.
Patch	Forest pixels include small forested areas surrounded by non-forested land cover.	($P_f < 0.4$). A pixel is part of a forest patch on a non-forest background, such as a small wooded lot within a built-up area.
Perforated	Forest pixels form the boundary between an interior forest and relatively small clearings (perforations) within the forested landscape.	($P_f > 0.6$ and $P_f P_{ff} > 0$). Most pixels in the surrounding area are forested, but the center pixel appears to be part of the inside edge of a forest patch. This would occur if small clearings were made within a patch of forest.
Edge	Forest pixels define the boundary between interior forest and large nonforested land cover features.	($P_f > 0.6$ and $P_f P_{ff} < 0$). Most pixels in the surrounding area are forested, but the center pixel appears to be part of the outside edge of a forest. This would occur along the boundary of a large built-up area or agricultural field.
Transitional	Areas between edge type and non-forest types. If higher pixels are non-forest, they will tend to non-forest cover with a higher degree of edge.	($0.4 < P_f < 0.6$). About half of the cells in the surrounding area are forested and the center forest pixel may appear to be part of a patch, edge, or perforation depending on the local forest pattern.
Non-Forest	Areas covered by anthropogenic landscape elements (such as buildings, roads, agricultural fields, and barren land) other than natural vegetation	Depicts the intensity of disturbances.
Water	Streams, Rivers, Ponds, Lakes	Considered as non-fragmenting features, which form the natural corridors in a forested landscape, and support biodiversity

pixel changing from a LU category to other categories during time 1 to 2. This matrix is the result of cross-tabulation of the two images adjusted by the proportional error and is translated into a set of probability images, one for each LU category, which records a number of cells or pixels that are expected to change over the next time period.

The original transition probability matrix (denoted by P) of LU type is obtained from two former LU maps.

$$P(N) = P(N-1) * P \quad (4)$$

where, $P_{(N)}$ is the state probability of any time, and $P_{(N"1)}$ is the preliminary state probability. Transition area matrix can be obtained by,

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ \vdots & \vdots & \vdots \\ A_{N1} & A_{N2} & A_{NN} \end{bmatrix} \quad (5)$$

where A is the transition area matrix; A_{ij} is the sum of areas from the i^{th}LU category to the j^{th} category during the years from a start point to target simulation periods, and n is the number of LU types. The transition area matrix must meet the following conditions

i. $0 \leq P_{ij} \leq 1$

ii. $\sum_{i,j=0}^{n} P_{ij} = 1$

For example, the LU maps of the Mysore district for 1989, 1999, 2009, and 2019 were given as input for the Markov process. The transition probability and area matrices have been generated to evaluate persistency and transition from one LU to another from time 1 to 2, i.e., 1999-2009; 2009-2019. The constraints such as protected areas, water bodies are exempted from the change.

(iii) Spatial matrices

Spatial matrices computed include class area (CA), no of patches (NP), normalized landscape shape index (NLSI) and aggregation index (AI)

CA: Total land area in ha. Class area is calculated with respect to the number of cells present in a particular grid.

NP: NP can analyze the class's Compaction or Dispersion in a grid. Less NP value indicates the agglomeration of the class, and an increase in NP proves the scattering of the class.

NLSI: By considering the area and perimeter, NLSI calculates the area in the range of 0 and 1 where 0 is highly agglomerated and 1 is for highly scattered.

$$NLSI = \frac{\sum_{i=1}^{i=N} \frac{P_i}{s_i}}{N} \quad (6)$$

AI: AI value represents the grid's agglomeration and scattering of patches. Value ranges from 1 to 100 **(**Bharath et al., 2012**).**

$$AI = \sum_{i=1}^{m} \left(\frac{g_{ii}}{max \rightarrow g_{ii}} \right) * P_i * 100 \quad (7)$$

(iv) Prioritization of Ecological Sensitive Regions (ESR)

The process of identifying ESRs involved 4 steps: (i) identifying the significant factors that elucidate the ecological/environmental status or resources (Zhang et al. 2011, Liu et al. 2015); (ii) assigning weights based on the extent, condition and generating thematic spatial layers based on the environmental weights; (iii) generating aggregated weight by combining individual spatial layers (corresponding to bio-geo-climatic, hydrologic and ecological factors) by applying combination methods; (iv) prioritization of sensitivity of regions, based on the aggregate values (frequency distribution) into groups such as (a) highly sensitive and extremely sensitive, (b) moderately sensitive, (c) marginally sensitive and (d) not sensitive" (Leman et al. 2016, Ramachandra et al. 2018); and (v) assessing the integrated map, identifying ESRs and suggesting specific recommendations for prudent management towards sustenance of natural resources in the region (Gadgil et al. 2011, Ramachandra et al. 2019).

The study area is divided into 5'× 5' equal-area grids (73) covering approximately 9 x 9 km^2(equivalent to a grid in the Survey of India topographic maps of 1: 50000 scale) to account for the changes at the micro-scale. The data of various themes (bio, geo-climatic, ecological, social, etc.) were collected based on literature, unpublished datasets, and ground-based surveys (in the select representative grids). A detailed database of various themes with maps covering bio-geo-climatic, ecological, hydrologic, and social aspects for the district is developed through a grid-based environment survey. The weightage metric score is computed for each grid capturing various themes (Equation 8). Developing a weight-based metric score requires integrating information from a wide array of disciplines (Termorshuizen and Opdam 2009), aids in regional planning by actively integrating the present and future landscape needs (Ramachandra et al. 2017, 2018). The approach is based on the framework (Beinat, 1997) of eco-sensitive regions considering weights of chosen parameters, and it provides an objective and transparent system for combining multiple data sets to infer the significance. The weightage is given by equation 5,

$$Weighatge = \sum_{i=1}^{n} W_i V_i \quad (8)$$

Where n is the number of data sets (variables based on themes), Vi is the value associated with criterion i, and Wi is the weight associated with that criterion. An indicator describes each criterion mapped to a value normalized between 10 (high priority) to 2 (least). Values 8, 6 and 2 corresponds to high, moderate, low levels of conservation. Weights computed for each variable is aggregated for each grid, and grids are grouped into four categories as ESR 1, ESR 2, ESR 3, and ESR 4 based on the aggregated scores (considering mean(µ) and standard deviation (ό), as ESR 1: of grids with aggregate scores > µ+2ό, ESR 2 (for grids within µ+2ό and μ+ó), ESR 3 (for grids with μ+ó and μ) and ESR 4 (grids with values < μ). In particular, the weights are based on an individual proxy and depend extensively on GIS techniques, which is the most effective method.

RESULTS AND DISCUSSION

Assessment of landscape dynamics and fragmentation analyses

Spatio-temporal changes in the Mysore district landscape are assessed using temporal RS data (of 1989-2019) through GMLC to understand the anthropogenic pressure and the current status of forest cover. Figure 3 depicts land cover changes in the district. Figure 4 illustrates the LU changes, highlighting that the region has lost a significant portion of evergreen forest cover with increased horticulture and built-up areas (Table 2).

There has been a change in agricultural area from 64.4% (1989) to 68.6% (2019). Similar trend of increase is noticed in built-up (0.3% to 3.03%), horticulture (4.42% to 5.65%) and forest plantation (0.14% to 1.04%). The total forest area (dry deciduous and moist deciduous forest) has decreased from 1224.16 km^2 (1989) to 826.15 km^2 (2019). This decrease of forest area is noticed in the buffer zones of Nagarholé (Rajiv Gandhi National Park) and Bandipur Tiger Reserves. The policy push for eco-tourism has resulted in mushrooming of building in the buffer zone with the decline of the area under forests.

The built-up area has increased from 19.25 km^2 (1989) to 191.12 km^2 (2019). The main reasons for urban growth include an increase in population, formation of new residential layouts by Mysore Urban Development Authority (MUDA), private land developers and cooperative societies, industrial zones by the Karnataka Industrial Area Development Board (KIADB), resulting in the growth in real estate, establishment of IT (Information Technology) industries, emergence of educational/academic institutions, enhancement of road connectivity, infrastructure and development of industrial areas,

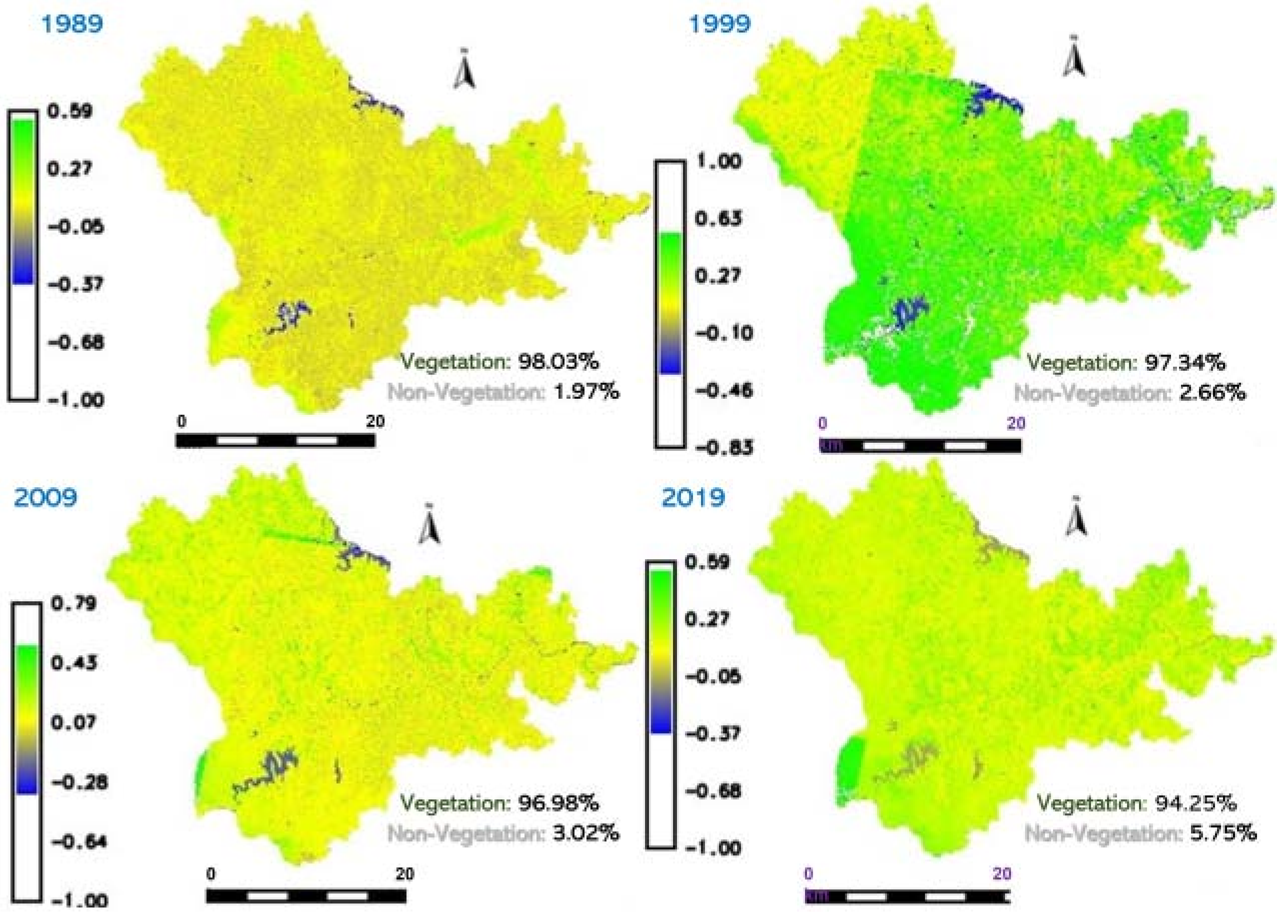


Figure 3. Land cover dynamics in Mysore district, Karnataka

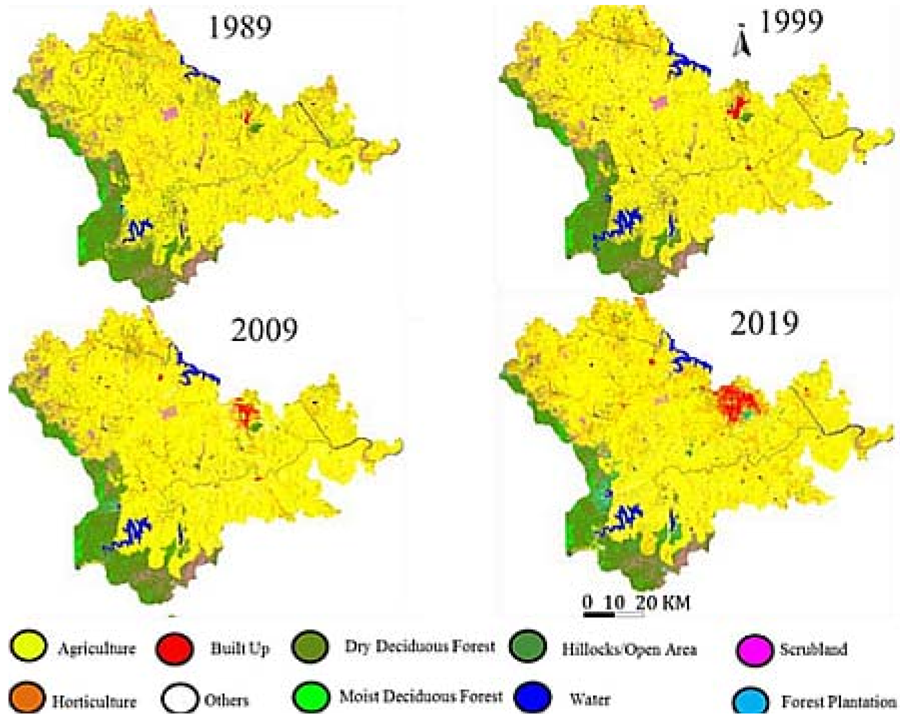


Figure 4. LU changes from 1989 to 2019

Table 2. Land use dynamics in Mysore

Category	1989		1999		2009		2019	
	Sq km	%	Sq km	%	Sq km	%	Sq km	%
Agriculture	4066.02	64.4	4119.00	65.24	4359.81	69.05	4331.16	68.6
Built Up	19.25	0.3	40.40	0.64	45.92	0.73	191.12	3.03
Dry Deciduous	1057.55	16.75	956.30	15.15	837.04	13.26	688.35	10.9
Hillocks/Open Area	132.28	2.1	68.43	1.08	65.43	1.04	63.94	1.01
Horticulture	279.02	4.42	312.19	4.95	307.70	4.87	356.71	5.65
Moist Deciduous	166.60	2.64	140.25	2.22	137.79	2.18	137.79	2.18
Others	-	-	130.50	2.07	126.95	2.01	158.81	2.52
Scrubland	506.50	8.02	380.54	6.03	280.79	4.45	153.20	2.43
Water	77.710	1.23	162.88	2.58	143.01	2.26	166.68	2.64
Forest Plantation	9.01	0.14	2.68	0.04	9.39	0.15	65.62	1.04

etc.

About 25,447 industrial units were registered in 2011, while in 1991, the registered industrial unit was only 8,661. The primary industries in Mysore are Bharath Earth Movers Limited (BEML) Ltd., Bank Note Paper mills India Pvt Ltd, TVS Motors. Consequent to the spurt in industrial activities, there has been an escalation in the built-up area from 0.7 % in 2009 to 191 km^2.

Table 3 lists category-wise overall accuracy and Kappa statistics done as part of accuracy assessment of the classification of remote sensing data. The field data and Google earth data sets are used for analyzing accuracy, and the analysis shows that accuracy ranges from 83% to 92%. Table 4 lists category-wise transitions of land usesfrom1989 to 2019, which indicates the agriculture class, which was 4066 sq km in 1989, is changed to 4331.16 sq km in 2019.

The total loss of forest cover in the district over four decades is about 388 km^2 (31.7%), highlighting the largescale mismanagement of the forest ecosystem in the district. This has led to the loss of carbon sequestration potential due to diminishing forest cover and increased emissions with intensified

Table 3. Accuracies and Kapa statistics of land use classification of temporal data - Mysore

Year	**1989**		**1999**		**2009**		**2019**	
Category	PA	UA	PA	UA	PA	UA	PA	UA
Agriculture	99.39	87.06	99.92	93.43	94.98	90.60	96.90	83.67
Built Up	35.74	100.00	92.65	95.44	85.93	94.28	71.96	92.45
Dry Deciduous	92.69	86.83	87.55	86.22	89.42	86.64	93.63	75.70
Hillocks	74.69	100.00	45.37	98.14	72.02	95.54	33.32	85.26
Horticulture	68.64	77.69	92.28	93.83	85.17	91.78	33.98	45.96
Moist Deciduous	96.31	98.50	51.94	99.51	25.49	100.00	87.46	77.46
Others	-	-	61.81	97.07	93.68	100.00	44.90	90.09
Scrubland	26.00	97.31	43.52	51.17	61.67	47.12	55.97	97.55
Water	99.99	99.96	98.04	99.85	99.48	89.38	86.36	95.15
Forest Plantation	35.44	94.17	-	-	-	-	65.96	80.58
	OA	87.79	OA	92.44	OA	87.99	OA	82.96
	KAPPA	0.79	KAPPA	0.84	KAPPA	0.82	KAPPA	0.89

Note: OA: Overall accuracy, PA: Producer accuracy, UA: User Accuracy

Table 4. The transition of land use class from 1989 to 2019

Land use of	**Land use transitions during 1989 and 2019**										
1989	AG	BU	DD	HI	HO	MD	OT	SL	WT	FP	**1989**
Agriculture (AG)	3475.2	149.8	0	31.33	215.51	0	123.1	0	63.2	8.02	**4066.3**
Built Up (BU)	10.5	5.62	0	0.12	0.49	0	0.60	0	1.70	0.15	**19.24**
Dry Deciduous (DD)	233.4	5.85	688.35	19.34	32.78	0	13.71	0	15.7	48.11	**1057**
Hillocks (HI)	110.3	8.15	0	1.81	5.27	0	5.38	0	0.93	0.38	**132.26**
Horticulture (HO)	205.4	9.61	0	2.21	47.91	0	4.37	0	9.07	0.41	**278.96**
Moist Deciduous (MD)	19.9	0.28	0	0.26	4.38	137.8	0.27	0	3.40	0.08	**166.49**
Others (OT)	0	0	0	0	0	0	0	0	0	0	**0**
Scrubland (SL)	261.6	11.73	0	8.36	48.99	0	10.88	153.2	3.86	7.87	**506.56**
Water (WA)	9.6	0.12	0	0.06	1.01	0	0.06	0	66.6	0.01	**77.44**
Forest Plantation (FP)	5.1	0.02	0	0.41	0.340	0	0.37	0	2.15	0.56	**8.98**
2019	**4331.1**	**191.1**	**688.35**	**63.94**	**356.71**	**137.8**	**158.8**	**153.2**	**166.7**	**65.62**	**6313.4**

industrial activities (Ramachandra and Bharath 2021).

Fragmentation of forest for 1989, 1999, 2009, and 2019 was assessed to understand the health of the forests with the help of the temporal LU information, considering the area under different categories of forests, which includes moist deciduous, scrub, dry deciduous forest areas and this excludes forest plantations (acacia, teak, others). The analysis reveals the decline of interior forest (11.52% to 9.4%) with an increase in a perforated forest (1.15% to 3.56%). Figure 5 gives the spatial extent of forest cover loss in the study area. Table 5 gives class-wise changes in forest cover structure from 1989 to 2019.

The other classes like patch, transitional and edge decreased from 2.05, 1.75, and 2.1% (1989) to 1.99, 1.2 and 0.86 (2019), respectively. The fragmentation is more prevalent in the buffer zone of Bandipur National Park, Nagarholé Tiger Reserve (Rajiv Gandhi National Park), and HD Kote taluk due to the increase in eco-tourism activities.

The loss of interior forest cover has altered the hydrologic regime and induced higher soil erosion triggering landslides and increasing human-animal conflicts.

Modeling and visualization of landscape dynamics

The LU analyses provided insights into the transition

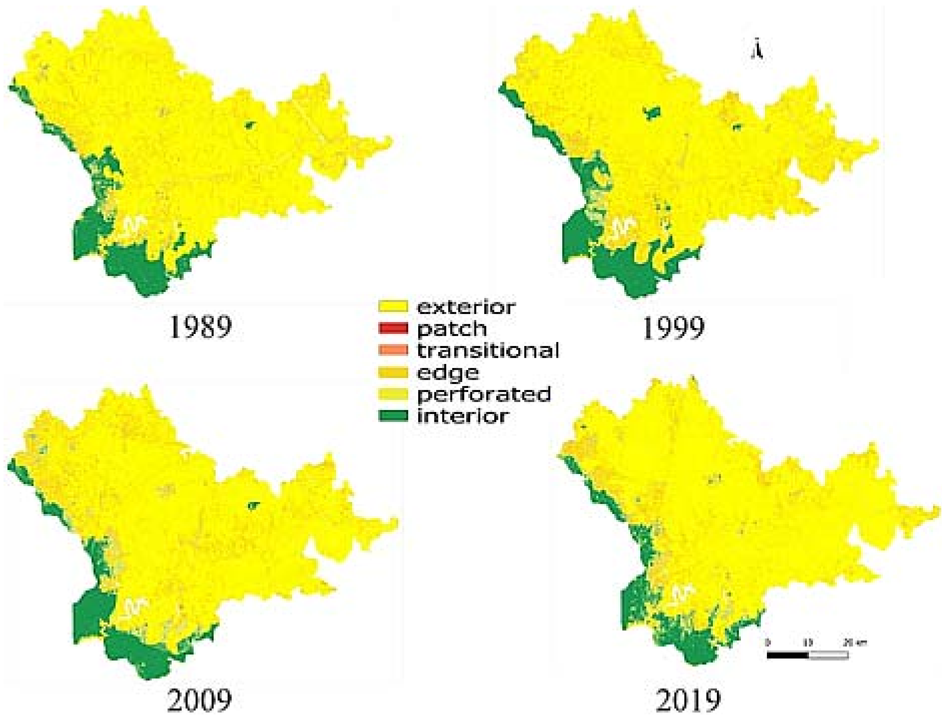
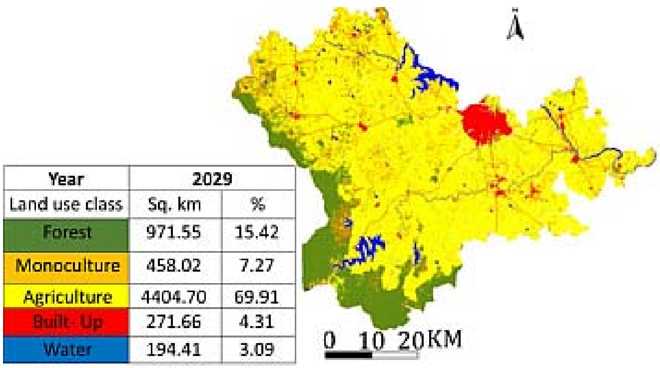


Figure 5. Spatiotemporal fragmentation of forests from 1989 to 2019



Year	2029	
Land use class	Sq. km	%
Forest	971.55	15.42
Monoculture	458.02	7.27
Agriculture	4404.70	69.91
Built- Up	271.66	4.31
Water	194.41	3.09

Figure 6. Predicted land uses in Mysore during 2029

of forest cover from 1989 to 2019. Modeling of the landscape has been carried out to understand the impact of the current rate of LULC transitions in the near future with the help of Markov and Cellular Automata techniques. Predicted land use for 2029 is given in Figure 6.

Simulated land use details highlight the agricultural land likely to increase from 4331.16 km^2 (2019) to 4404.702 km^2 (2029). The built-up area is expected to increase to 3.03% (2019) from 4.32% (2029). Degradation of the forest will continue with a further decline in forest cover from 15.51% (2019) to 15.42% (2029).

Landscape metrics

The spatial pattern of forest structure at decentralized level (9 X 9 km grids) were assessed through the computation of spatial metrics, namely class area, normalized landscape shape index (NLSI), aggregation index, for 1989, 1999, 2009, and 2019, which are depicted in Figure 7. The analysis reveals

(i) a decrease in the forest area (8000 ha to 7600 ha) from 1989 to 2019. The main changes are around the Mysore city and Bandipur forest area.

(ii) The number of patches indicates the extent of fragmentation in the landscape with value 0 indicating clustering of patches into a single built-up patch while value 1 indicates the increase in the fragmentation. The study shows an increase in the number of patches in central Mysore.

(iii) A decrease in AI value indicates of ungrouping, especially along the taluks of Mysore, H D Kote and Periyapattna.

(iv) NLSI indicates that the values around the Nanjangud, Periyapatna, and H D Kote increased, depicting the forest cover decline.

Ecological Sensitive Regions in Mysore district at the disaggregated level

Prioritization of Ecological Sensitive regions (ESR)in the Mysore district is determined by

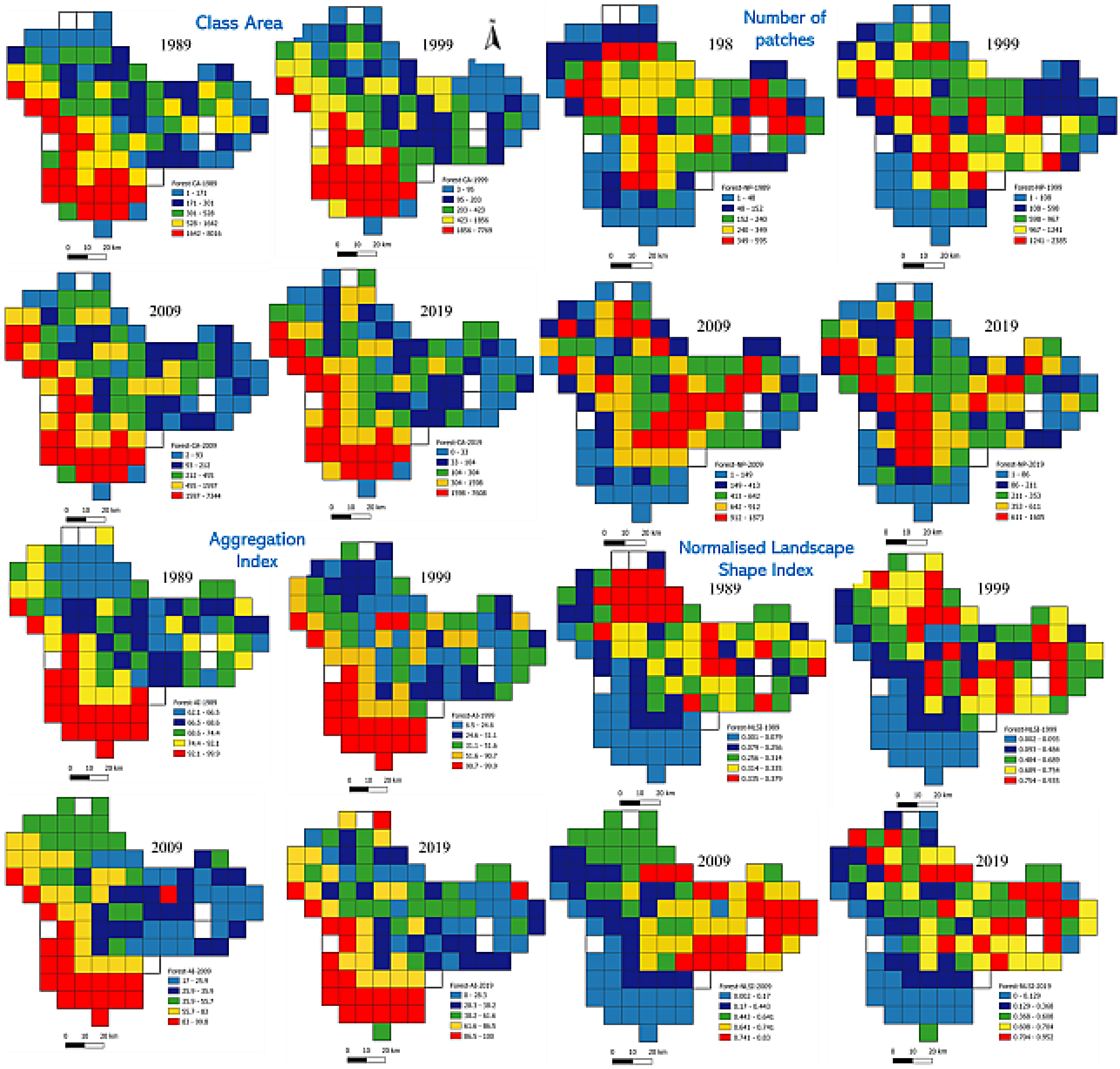


Figure 7. Spatial patterns of landscape structure for forest class

integrating bio-geo climatic, hydrologic regime, ecological and social variables at grid levels. The integration of diverse information of various themes at disaggregated levels helped to prioritize regions for conservation with prudent management. Table 6 provides weights assigned to a variable based on the spatial extent and condition.

Figures 8a,b depicts the forest cover and interior forest cover status. Forest cover is higher at Bandipura, Nagarholé reserved forests and significantly less (<15%) in the other parts of the Mysore, and weights were assigned based on the cover and health. The information (spatial distribution) of the flora and fauna species across the district was compiled through field sampling and literature review (KFD 2020, Ramachandra and Bharath 2019). The distribution of the species endemic to the threatened species (according to the IUCN Conservation Status) has been analyzed, which are concentrated in the grids in and around Bandipura, Nagar holé reserved forests (Figs. 8c,d). Figure 8e highlights higher biomass in Bandipura and Nagar holé reserved forest and least in the urban areas. The grids covered by protected areas of the district were assigned a higher weight of 10, as depicted in Figure 8f.

Table 6. Theme-wise allocation of weights for bio-geo-climatic variables depending on extent and condition

Sl no.	Theme	Variable	Weight				
			2	**4**	**6**	**8**	**10**
1	**Land**	**Forest Cover**	<15%	15-30%	30-45%	45-60%	>60%
		Interior Forests	<15%	15-30%	30-45%	45-60%	>60%
2	**Geo-climatic**	**Agro-Climatic Zone**	-	-	-	Southern Dry Zone, Hot Humid	The Western Ghats, Hot Moist Sub Humid
		Altitude (m)	-	<250	250-500	500-750	>750
		Slope (%)	-	N.A	N.A	>15	>30
		Rainfall (mm)	<600	600-1200	1200-1800	1800-2400	>2400
		Soil	Coarse Loamy	Sandy or Sandy Skeletal	Fragmental or Rocky outcrops	Clayey Loamy or Clayey Skeletal	Loamy or Clayey
		Lithology	-	Charnokites or Kalaadgi	Peninsular Gneiss	Dharwars or Granite	Deccan Trap
3	**Ecology**	**Flora**	Non-endemic	Endemic/ Threatened	Endemic/ Threatened flora < μ and μ	Endemic/ Threatened flora $\mu+\sigma$ and $\mu+\sigma$	Endemic/ Threatened fauna> $\mu+2\sigma$ fauna $\mu+2\sigma$
		Fauna	Non-endemic	Endemic/ Threatened flora < μ	Endemic/ Threatened flora$\mu+\sigma$ and μ	Endemic/ Threatened fauna $\mu+2\sigma$ and $\mu+\sigma$	Endemic/ Threatened fauna> $\mu+2\sigma$
		Protected Area (PA)		0 was assigned to grids outside PA			10 was assigned to the grids within PA
		Biomass (Gg)	<300	300-600	600-900	900-1200	>1200
4	**Hydrology**	**Stream Density**	<0.5-1	1-1.5	1.5-2	2-2.5	>2
		Stream Flow	3 months	3 months	4 months	5 months	>6 months
5	**Energy**	**Solar (KW/h)**	-	-	-	< 6	>6 KW/h
		Wind (m/sec)	1.5	1.5-2	2-3.5	3.5-4	>4
		Biomass	-	230000	230000-360000	360000-660000	>660000
7	**Social**	**Population Density (ind/ha)**	>1000	500-1000	250-500	100-250	<100
		Livestock Density (animals/ha)	<0.75	0.75-1.5	1.5-2.25	2.25-3	>3

Digital Elevation Model (DEM) map observed the range of more than 1000m and between 500 to 750 m all over the district (Fig. 9a). Slope weight has been assigned based on sensitiveness as disturbing greater slopes tend to result in disasters (Fig. 9b). The precipitation map shows an increase of rainfall from northeast to southwest, ranging from 1800-2400 mm (Fig. 9c). Lithology (peninsular, Dharwad granite) and soil (clayey, loamy, etc.) found in the region were accounted and its variability as depicted in Figures 9d,e. Weights were assigned to grids based on the significance of variables (extent and condition). The duration of streamflow is higher in the catchment of Nagarholé and Cauvery River, with higher stream densities (Figs. 10a,b). Population Density information is taken from the 2011 census and a higher population density of 1000 persons per hectare in the Mysore urban area (Fig. 10c). The livestock density (LD) distribution map shows KR Nagar has a higher density of livestock (2.25-3) (Fig. 10d). Solar energy, wind energy, bioenergy potentials were assessed based on the earlier assessment

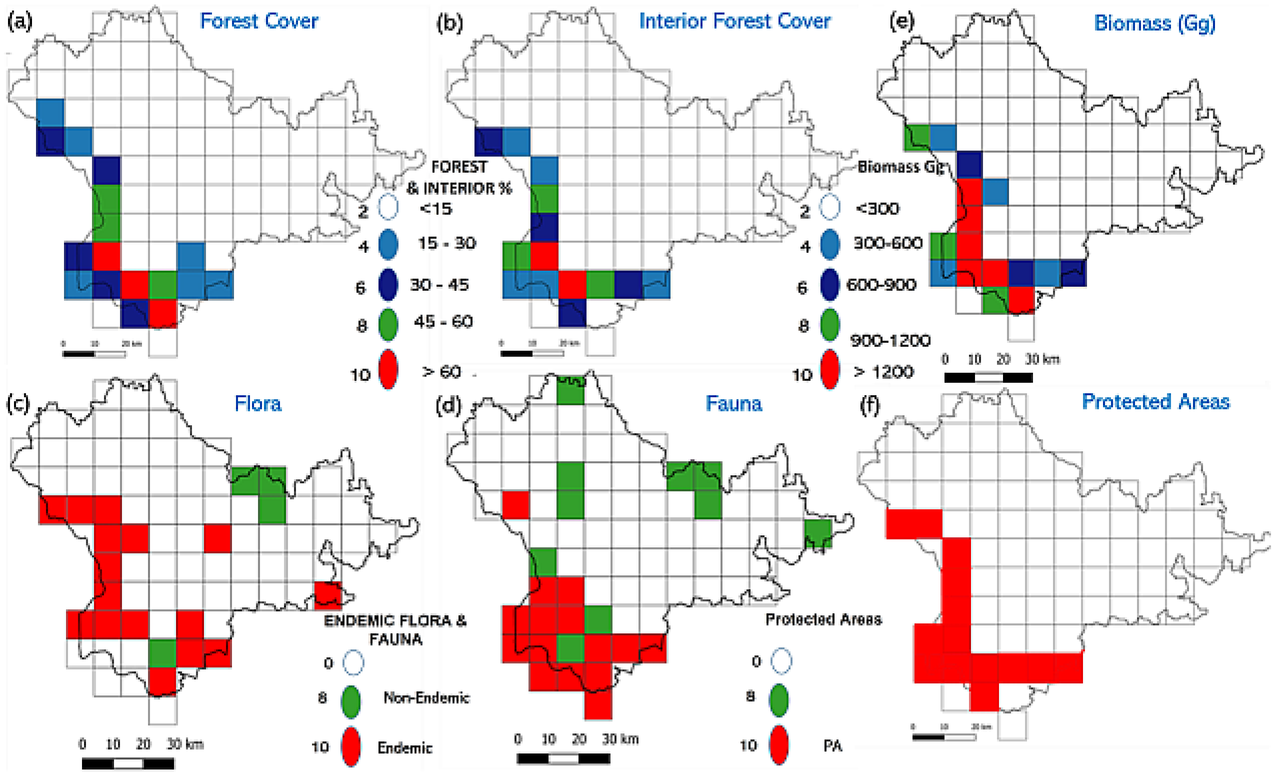


Figure 8. Weights and ranges for land and ecology factors

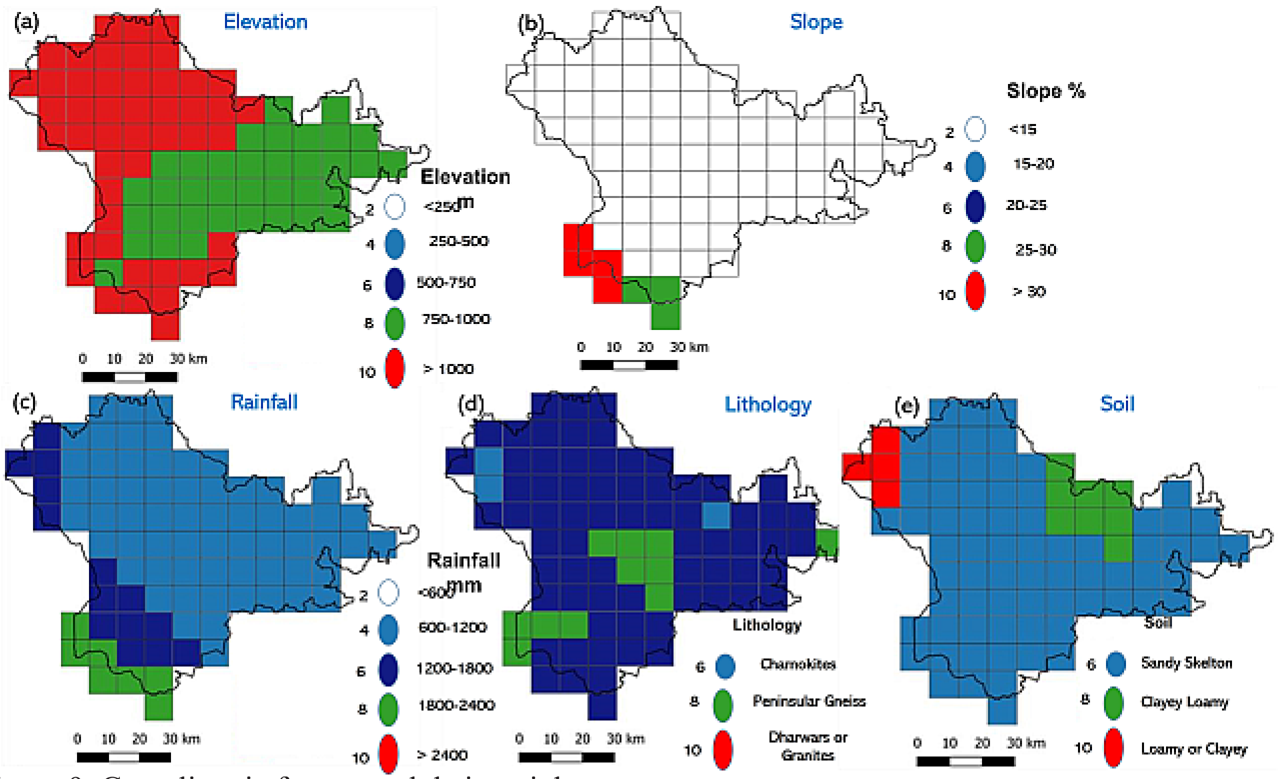


Figure 9. Geo-climatic factors and their weights

(Ramachandra and Hegde 2014), and the weight is assigned based on the potential (Figs. 11a-c).

The ESR assessment is a qualitative and quantitative analysis of the significant ecological and environmental factors crucial for socio-economic activities. The weights assigned to the grids (based on the relative strengths of themes considering bio-geo-climatic, hydrologic regime, ecological and social aspects) and these grids are aggregated, and the composite weights of these aggregated scores

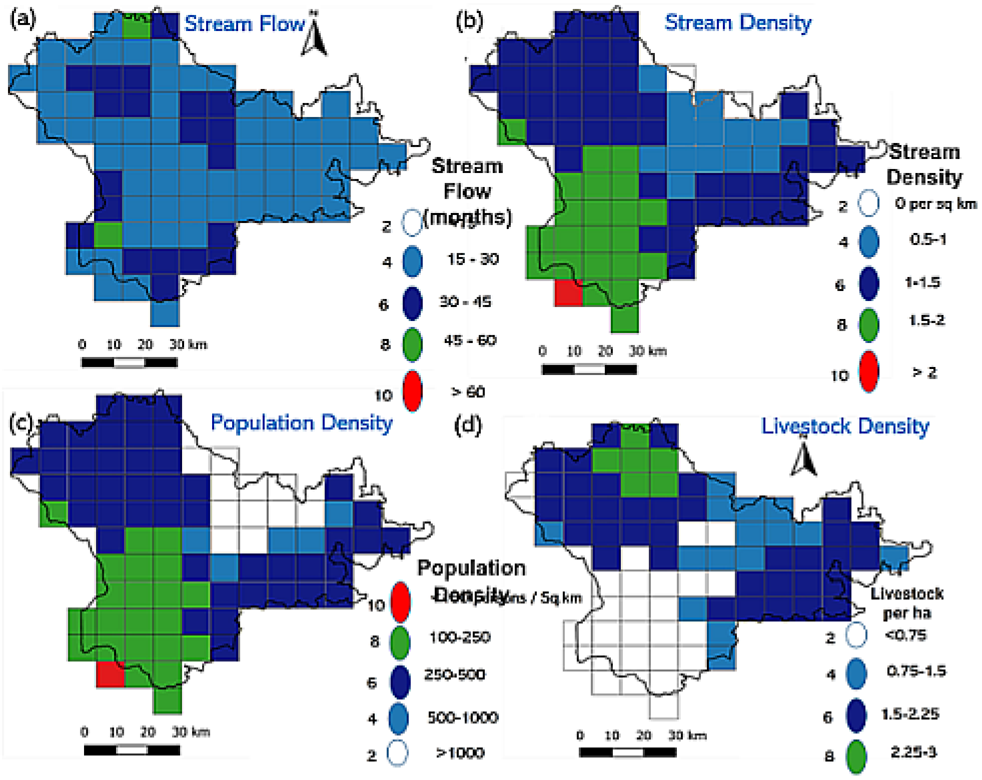


Figure 10. Hydrology, social factors, and their weights

were assessed statistically (frequency distribution considering (mean ± μ standard deviation, where μ ranges from 1 to 2) to group grids based on the composite metric into four groups to designate as ecologically sensitive regions (ESR) 1, 2, 3, and 4, respectively.

Figure 10 highlights that 1134 sq km in the district falls under ESR1 (14 grids), 1458 sq km falls under ESR 2 (18 grids), 3888 sq km falls under ESR 3 (48 grids), and 162 sq km falls under ESR4 (2 grids). Table 7 lists the spatial extent of the areas under each zone. ESR 1 is to be treated as a susceptible region, and stringent conservation measures are to be imposed by regulatory authorities through an inclusive approach involving VFCs (Village forest committees), BMC (Biodiversity Management Committee at Panchayath). ESR 2 represents a zone of higher conservation and forms a transition for the stringent conservation and moderate conservation regions. ESR 2, with the implementation of conservation protocol, has the potential to attain the status of ESR 1. A small change in ESR 2 will have more adverse effects in ESR 1. ESR 1 and ESR 2 cover all reserve forests, wildlife sanctuaries (Nagarholé and Bandipur), and river catchment areas (Cauvery, Kabini, etc.). That signifies that significant urbanization has not happened in that area, so the natural resources are rich. ESR 3 represents a moderate conservation region, and only regulated development is allowed in these areas. This region is predominantly under croplands and horticulture land use, and only small-scale industries such as Nanjangudu, K R Nagara, T N Pura are present. ESR 4 is the region where urbanization has happened, and major industries that use most of the resources are present.

Table 7. Ecologically sensitive regions – category wise spatial extent

Ecologically sensitive regions	No of grids	% area
ESR1	14	17.07%
ESR2	18	21.95%
ESR3	48	58.5%
ESR4	2	2.43%

In ESR 2 and ESR 3, further developments are allowed only after critical review by the regulatory authorities in consultation with the local stakeholders. Small-scale tourism such as homestay

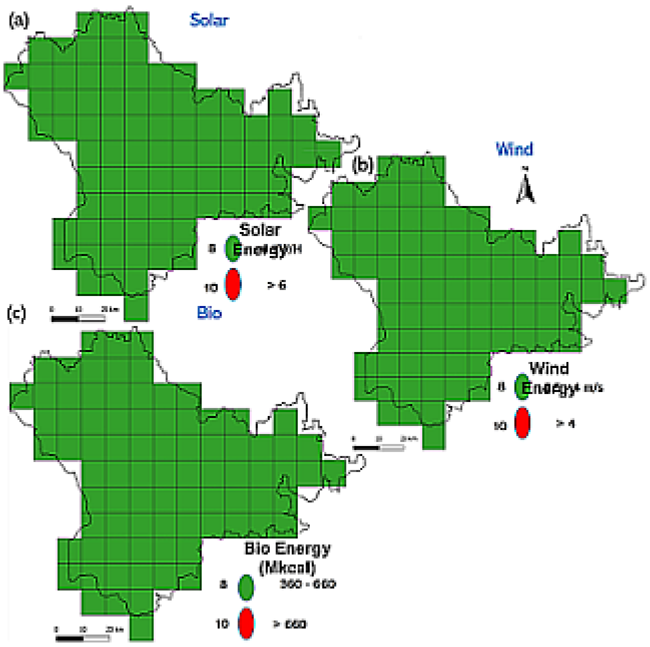


Figure 11. Energy prospects of Mysore, weights

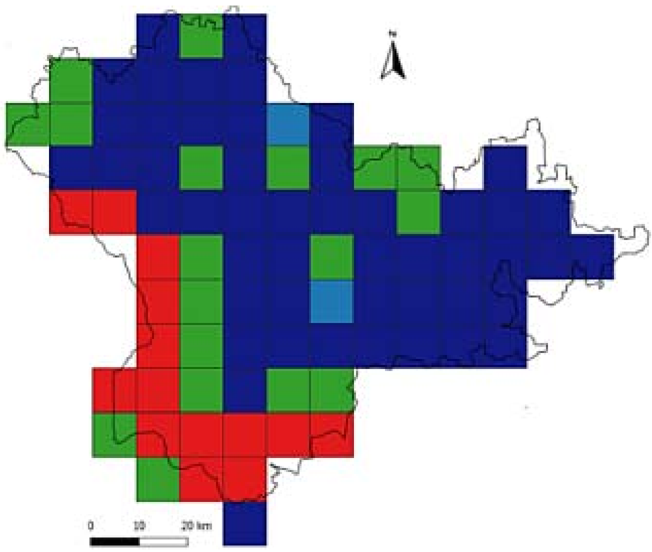


Figure 12. Ecological Sensitive Regions of Mysore

(without any large-scale construction activities), spice farms, eco-friendly boating, etc., could be encouraged by adopting a benefit-sharing approach with local communities. The unregulated development, including infrastructure projects, needs to be restricted in and around pristine lakes, primeval forest patches, perennial water bodies. The site-specific (cluster approaches in the development path to enhance job opportunities and optimization of local resources use) sustainable developments can be taken up at each panchayat level, with the most negligible effects on the ecosystem.

ESR 4 represents the least diverse areas, and the developments are allowed as per the requirement of local people through strict vigilance of regulatory authorities. It is recommended that these regions also have a lot of scope for further enrichment of the environment by stakeholders and forest department intervention. Permissible activities in various ESRs, recommended in the conclusion section while ensuring ecological integrity (Ramachandra et al. 2018).

CONCLUSIONS

Assessment of spatial patterns of land uses and modeling probable land-use changes in a region aided in understanding landscape dynamics. Temporal land use analyses showed a decline of 6.3% forest cover (1989 to 2019) due to the implementation of infrastructure projects, agricultural activities (increased by 4.2%), industrialization, urbanization, etc. Fragmentation analysis reveals loss of interior forest by 2.12%. Modeling of the likely LU changes reveals increased built-up by 1.29% and agriculture by 1.31% during 2019 - 2029. Computation of spatial matrices proves the higher urbanization and loss of forest cover in the outskirts of city centers. Delineation of ecologically significant regions helps in framing policies and regulating activities toward prudent management of land resources through active participation of the stakeholders. ESR is prioritized based on bio-geo-climatic, ecological, and social parameters at decentralized levels by dividing the study region into 5’ x 5’ (or 9 km x9 km) grids as per NES, which indicates that 14 grids came under ESR1 (which are mainly in the Bandipura and Nagarholé areas).

The current research recommends stringent protection measures in the ecologically sensitive regions ESR 1 and 2, while ESR 3 represents a moderate conservation region, recommended for the regulated development based on a proper review of environmental impacts by authorities. ESR 4 represents the least diverse region, and development may be allowed as per the requirement of stakeholders under the strict vigilance of regulatory authorities. The region-specific cluster-based approaches in the development path to enhance job opportunities and optimize the use of local resources at each panchayat level, with the least effects on the ecosystem. The comprehensive endorsement of a region into distinct ESRs proposed here based on a composite metric by accounting for many aspects such as bio-geo-climatic, ecological, and social factors will aid the government and regional managers in framing environmental policies crucial for sustainable development and maintaining a stable ecological environment.

Recommendations

Mysore district is located at the foothills of the Western Ghats with exceptional biodiversity. The expansion or construction of new linear alignments would result in irreversible ecological degradation. The recent floods and landslides in the region are certainly alerting the decision-makers of likely implications with the drastic changes in the land cover eroding the native forest ecosystems. Further interventions will worsen the ecology and hydrology as well as livelihood with the increase in the instances of human-induced calamities – landslides, mudslides, floods, droughts, etc. Hence following are the recommendations for conservation and management (Ramachandra et al. 2018) of these forests.

· The region is intrinsically fragile with steep slopes and sharp gradients; small disturbances will lead to catastrophe. Deforestation needs to be arrested immediately through strict regulation and social audit.

· Forest Rights Act to be implemented scientifically (using spatio-temporal data) in its true spirit and reaching out to people.

· Strict regulations are required to regulate tourism activities and a number of tourists per season. The tourism Master Plan should be based on MoEFCC (the Ministry of Environment, Forests and Climate Change, Government of India) regulations (after taking into account social and environmental costs).

· A strict ban on plastics and solid waste dumping in forest areas and ecological fragile riverine ecosystems should be implemented with higher penalties.

· The physical and chemical integrity of water bodies is to be ensured through the implementation of stringent regulatory norms. River diversion should not be allowed in the district.

· Large, medium, and micro-scale hydroelectric projects should not be allowed.

· The quarries (existing even in steep slopes) and uncontrolled illegal sand mining are to be regulated for protecting streams, natural resources in the district.

· The district administration should restrict the unauthorized occupation of forest areas by illegal immigrants and commercial farming (ginger cultivation).

· Monoculture plantations are not allowed; existing exotics should be replaced by planting endemic species both in evergreen and deciduous forests. Teak monoculture planting in Nagarholé has to be stopped and promotion of native species plants (food and fodder) reforestation.

· Due to scarcity of food and fodder trees and plants, wild animals, including elephants, often spend more time in coffee plantations and croplands, escalating human-animal conflict and loss of crops. Hence, more and more prominence has to be given to plant fruiting trees and fodder plants used by wild animals for their food and fodder requirements instead of non-food trees.

· The large degraded deciduous forest patches have to be compartmentalized block-wise and planted with native species, protected from grazing by both cattle and wild animals by laying proper trenches or fences. Large-scale collection of commercial firewood, poles, and illegal logging has to be immediately curtailed.

· There should be effective village-wise VFCs (Village forest committee) not only for safeguarding but also for promoting the quality of forests.

· Women self-help groups, youth, and tribes should be engaged in creating nurseries and afforestation programs. The schools, colleges, and local people should be involved in forest enrichment with native species and awareness workshops.

· Removal of all encroachments and restoration of forest integrity through planting of native species in the ecologically sensitive regions (ESR 1 and 2).

· The government needs to take appropriate mitigation measures in the animal movement paths and PAs by (i) creating water bodies, (ii) growing fodder crops, (iii) restrictions on inappropriate crops, and (iv) eviction of unauthorized occupation of forest lands.

- Proper training and awareness have to be given to forest department personnel such as watchers and guards to identify trees and plants for conservation.
- Improved connectivity and reduced fragmentation will aid species conservation. The connectivity between forest patches should be established by enriching native forest cover (biological corridors) that allow species to move and genes to flow from one patch to another.
- Enrich the grasslands, grassy patches with native grass varieties (e.g., *Cynodon dactylon, Oplismenus burmanii, Arundinella leptochloa, Panicum auritum*, etc.) to improve herbivorous population.
- Regulated traffic movement at night in order to mitigate roadkill of wild fauna.
- Promote decentralized electricity, use of renewable energy sources such as (solar, wind power). The local bio resource-based industry should be promoted. All need to be strictly regulated and be subject to social audit.
- Adapt development projects which will have the least environmental impact by involving local community members in the decision-making and environmental monitoring.
- Uncontrolled development should be discouraged in and around pristine lakes, primeval forest patches, perennial water bodies. The site-specific (clustered-based) sustainable development path to be adopted at each panchayat, which has the most negligible effects on the ecosystem.

DATA AND ACCESSIBILITY

Data used in the analyses are compiled from the field. Data is analyzed and organized in the form of table, which are presented in the manuscript. Also, synthesized data are archived at http://wgbis.ces.iisc.ernet.in/energy/water/paper/researchpaper2.html#ce; http://wgbis.ces.iisc.ernet.in/biodiversity/

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Authors' contribution: All authors contributed equally

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