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Prioritization of natural resources rich regions (NRRZ) based on ecosystem (biotic and abiotic) extent and conditions

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Abstract
Ecosystems are distinct biological entities characterized by a range of functions. The integrity of the ecosystem is vital for sustaining ecosystem goods and services to support people's livelihood. Maintaining ecosystem integrity requires ecosystem approaches in managing natural resources considering dynamics due to natural variabilities and anthropogenic activities. Sustainable developmental planning focuses on the efficient and innovative use of regional resources, with an improved understanding of social and environmental interactions. The comprehensive knowledge of a region's ecological sensitivity/fragility is quintessential for evolving conservation strategies. Ecosystems' ecological sensitivity refers to ecosystem stability, persistence, resilience, and recovery properties to overcome environmental disasters, which are likely to affect natural landscapes' character adversely. The ecologically sensitive regions are natural resources-rich zones (NRRZ) endowed with distinct biological elements with geological, physical, and chemical characteristics. Spatial integration of geo-climatic, ecological, environmental, and social variables helps delineate NRRZ for prudent management of natural resources through ecological and conservation planning as per the Biodiversity Act, 2002, Government of India. NRRZ delineation has been done at disaggregated levels (9 km x 9 km grids) considering ecological, bio-geo-climatic, social, and environmental aspects compiled from field and published literature, and prioritization of NRRZ (as NRRZ 1 to 4) has been done through aggregated weightage metric score (of chosen variables per grid). The novelty of the current study is the prioritization of NRRZ at disaggregated levels (grids of 5' x 5' or 9 km x 9 km, equivalent to a grid in 1:50000 topographic map of the Survey of India) and also the decentralized governance unit- Panchayat through the integration of diverse multi-dimensional bio-geo-climatic, environmental and social factors. The strength of NRRZ is the replicability for prudent management of natural resources and real-world conservation governance. 32% of the state's geographical area was depicted as a high-resource region under NRRZ 1 and 2, which needs to be conserved with stringent regulations. Prioritizing regions as NRRZ by integrating spatial data (land cover) with location-based attribute information would strengthen regional decision-making.

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1 Introduction

Natural Resources are the biotic and abiotic resources, including soils, water, animals, and plants, responsible for producing goods to meet anthropogenic and other biota needs and accountable for maintaining ecological functions. An ecological system is a complex system containing multiple interacting elements, with feedback and nonlinearities characterized by spatiotemporal interactions (Burkett et al., 2005). Natural resources are responsible for the long-term productive potential of nature, maintenance of their environmental functions, and commercial development. With the maintenance of ecological values, the forest ecosystem sustains the balance of abiotic and biotic variables; imbalance may induce irreplaceable loss to humankind and nature (Ramachandra et al., 2016). Altering the ecological integrity through uncontrolled exploitation of resources would impact the ecological goods and services, thereby affecting the livelihood of the dependent population. Development approaches for economic advancement need to consider social, ecological, psychological, and political processes to improve the dependent population's quality (World Bank, 2006; Ramachandra et al., 2024). Unplanned and unsustainable economic activities may provide employment and resources to the handful of influential sections but deprive most of the native population of natural resources. The uncontrolled manipulation of the natural landscape due to land use changes has resulted in fragmentation and degradation of forests, deforestation, the release of higher carbon content to the atmosphere, the spread of exotic species, hydrological imbalances, frequent floods with droughts, higher soil erosion, etc., with a decline of sustenance of natural resources (Rawat et al., 2013; El Baroudy & Moghanm, 2014; Ramachandra et al., 2016; Davis, 2016; Ramachandra & Bharath, 2019). This entails effective natural resource management of a region by integrating sustainable development with the use of forest resources by maintaining ecological values. Natural resources form an integral part of the development of a region supporting various sectors, thereby supplementing various growths such as population, income, and employment with various amenities (Rupasingha & Goetz, 2004). The modern growth or development theory ignores the significance of natural resources and does not include their status as part of growth. However, a general understanding of the significance of natural resources in relation to growth and their support in providing various amenities are being acknowledged due to their importance in attracting economically prosperous status. Identifying such invaluable amenities by local agencies is vital for the sustenance of resources. In this context, policymakers need to understand the implications of earlier decisions with the current status to evolve appropriate management strategies to support economic growth with the sustainability of resources.

Natural resource management encompasses resource evaluation, land use planning with insights into landscape dynamics, and the systematic assessment of current potential and alternatives for optimal resource use with improved economic and social conditions through participatory processes covering multisector and stakeholder perspectives. Natural resource management and ecological protection need to integrate cross-scale interactions of the socio-ecological system (Peters et al., 2007), which are sensitive to climate variability and change (Ramachandra et al., 2018). Changes in the availability of resources need to be estimated, which is highly relevant in understanding and managing the system. Earlier studies attempted to map conservation zones based on the sector, such as biodiversity conservation, watershed management, sustainable development, and urban planning. Aragão et al. (2017) proposed a framework for sustainable land management and conservation efforts based on insights into temporal land use leading to land degradation and deforestation in the Amazon basin. Duvail et al. (2006) advocated a participatory mapping for the local management of natural resources in villages of the Rufiji district (Tanzania) through GIS-based Village Environmental Management Plans (VEMP). Tallis and Polasky (2009) have used the Integrated Valuation of Ecosystem Services and Tradeoffs tool (InVEST) to map multiple ecosystem services and biodiversity, the ability to focus on ecosystem services to identify the rich ecosystem zones, and improve decision-making. Using ecological and socio-economic data, Dawson et al. (2018) prioritized natural resource zones for sustainable development. Dhiman et al. (2019), through geospatial technology and a multi-criteria decision-making approach, proposed a Coastal Area Index (CAI) using land use land cover (LULC), digital elevation model (DEM), normalized difference vegetation index (NDVI) and coastal slope (%).

Natural Resource Rich Zones (NRRZ) identification and prioritization provide crucial information on the status, condition, and trends related to resources and form a base for decision-making. NRRZ identification is an integral component of an ecological regional planning approach, which plays an increasingly important role in nature conservation policies and strategies (Smith & Maltby, 2003). The prioritization also incorporates functional conservation networks (protected natural areas and buffer zones) and other elements in the landscape matrix (Bennett, 1999; Bennett & Mulongoy, 2006; Gurrutxaga et al., 2010). However, identifying and producing reliable and actionable approaches for protecting natural resources in ecologically sensitive areas is crucial for planning and management. Identifying and mapping NRRZ provides strong evidence to guide real-world decisions impacting local, regional, and global scales. Identifying and protecting NRRZs will safeguard the landscape from alteration of the natural topography, deforestation, soil erosion, loss of soil nutrients, sedimentation, soil compaction, spread of invasive exotic species, fragmentation of forests, human-animal conflicts, etc. Prioritizing NRRZ, considering the importance of humans and other biotas, will provide a strong foundation for decision-making endeavors with less time. In this regard, the objective of the current study is to prioritize regions at disaggregated levels of resource-rich Karnataka state based on the information on land, biodiversity, energy, and socio-variables (SEEA, 2017). This requires (i) quantifying landscape dynamics using spatial data collected from space-borne sensors, (ii) compilation of biodiversity and ecology information through field sampling and review of the literature (data mining), (iii) collating data of various natural resources and their status; and (iv) prioritizing NRRZs at decentralized levels (Panchayat level) towards sustainable management of natural resources.

2 Materials and methods

2.1 Study area

Karnataka is the most prosperous state located in the southwestern part of India, between 11˚34’ 33” and 18˚27’ 18” Latitude North and 74˚3’ 14” and 78˚ 34’ 37” Longitude East (Fig. 1), accounting for 5.83% of India’s total geographic area and eighth in India in terms of size. The state extends to about 750 km from North to South and about 400 km from East to West, covering about 1,91,796 square km. The population of the state was 61.1 million (as per the 2011 Census) and 68.26 million (2024) at a decadal growth rate of 9.4%. Karnataka has witnessed economic progress with information technology (IT), research, education, biotechnology, industrialization, agriculture, horticulture, and tourism. The state’s capital, Bengaluru, is known as the Silicon Valley of Asia due to its information technology (IT) and software industries. The Arabian Sea bounds the state on the west, Goa on the northwest, Maharashtra on the north, Telangana on the northeast, Andhra Pradesh on the east, Tamil Nadu on the south-east and Kerala on the south-west. It is situated on a tableland where the Western and Eastern Ghat ranges converge into the Nilgiris hill complex. Karnataka state consists of diverse forest types, such as tropical evergreen forests, shola forests, semi-evergreen forests, moist deciduous forests, dry deciduous forests, scrub and thorn forests, and mangrove forests due to diverse climatic, topography, and ecological conditions. These forests shelter numerous flora, animal, bird species, etc., and play a crucial role in the ecology and environment. The state has ten agro-climatic zones (North-eastern transition zone, North-eastern dry zone, Northern dry zone, Central dry zone, Eastern dry zone, Southern dry zone, Southern transition zone, Northern transition zone, Hilly zone, Coastal zone) based on physiography, soil types, and crops and cropping pattern. The state has seven agroecological zones based on physiography, soil, and bio-climate factors ranging from coastal areas to the Deccan plateau. The state receives an average annual rainfall of 1065 mm. The state’s geographical area is drained by seven river systems (Krishna, Godavari, Cauvery, North Pennar,

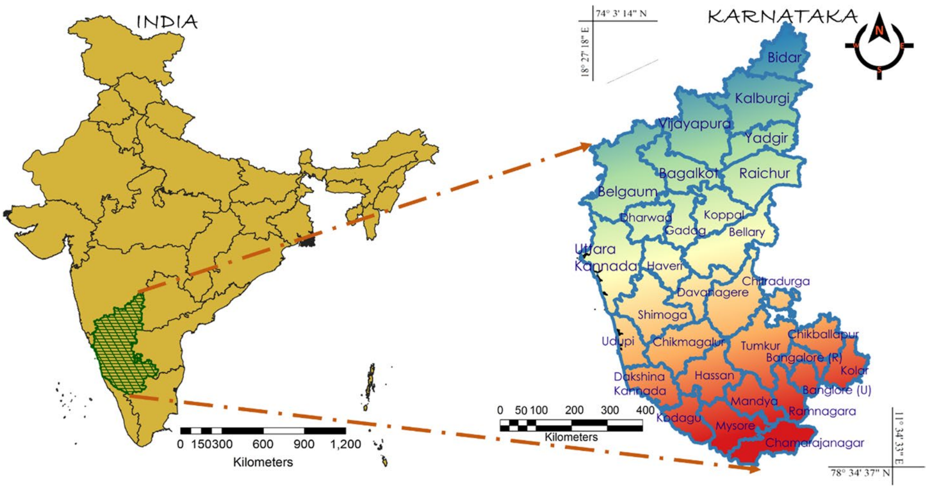

Fig. 1 Study area: Karnataka State, India

South Pennar, Palar, and assemblage of west-flowing rivers) and their tributaries. The major crops grown here are paddy, ragi, jowar, maize, pulses, oilseeds, etc.

2.2 Data

Identifying and prioritizing natural resource regions in Karnataka entailed assessing spatial data (remote sensing data) with collateral data, and field data related to biodiversity, ecology, carbon sequestration, etc. Table 1 lists the details of the data and method for prioritizing NRRZ (Fig. 2).

2.3 Method

Figure 2 depicts the protocol adopted for identifying NRRZs (Natural resource-rich regions, ecologically sensitive regions, or ecologically fragile regions) at decentralized levels in Karnataka state. This entailed (i) land use analyses, (ii) dividing the study region into 5' x 5' or 9 km x 9 km grids (equivalent to grids in the Survey of India topographic maps of 1:50000 scale), (iii) collating the biodiversity, ecology, hydrologic regime and social data from field and review of published literature, (iv) computation of aggregated weightage metric score and grading the NRRZs, and (v) prioritization based on composite metric through the integration of data of diverse themes.

2.3.1 Land use analysis

The spatial data acquired through space-borne sensors (satellite data) at regular intervals helped analyze LU changes and has an advantage in cost and accuracy. LU analyses using temporal remote sensing data form the base for understanding resource status and the basis for various resource availability (Bharath & Ramachandra, 2021). The temporal remote sensing data of Landsat series (TM, ETM+, OLI) of spatial resolution of 30 m were downloaded from the United States Geological Survey - Earth Explorer portal (https://www.usgs.gov/landsat). The data was pre-processed for geometric and radiometric corrections. The Landsat data is cost-effective, with high spatial resolution, and freely downloadable. Cloud-free data availability poses a significant challenge in land use analyses using remote sensing optical data. Cloud-free spatial data were downloaded from the public domain while ensuring a decade's data representativeness. The false colour composite (FCC) is generated using NIR, red, and green bands of spatial data, which helped identify heterogeneous patches corresponding to various land uses. The training data was digitized to correspond to these heterogeneous patches, covering 15% of the study region and uniformly distributed across the region. The attribute data of these training polygons were collected from the field using a pre-calibrated Global Positioning System (GPS) and virtual data portals (Google Earth (http://earth.google.com), and Bhuvan (http://bhuvan.nrsc.gov.in). Remote sensing data was classified through a supervised classifier based on the Gaussian Maximum Likelihood algorithm. Using free and open-source GRASS GIS software, 60% of field data is used for the LU classification. MLC is considered the most efficient and robust technique of supervised classification (Bharath et al., 2013, 2025; Ramachandra et al., 2018, 2024). The validation of classified LU information was done considering 40% of field data through computation of overall accuracy (error matrix) and Kappa statistics.

Table 1 Data and methods adopted for prioritizing NRRZ

Ecosystem Condition Indicator	Method	Data Source	Reference or Target condition/ State variable	Scope
Ecosystem Extent	Land use (LU) analyses using supervised classified based on the Gaussian Maximum likelihood algorithm	Land use data based on temporal remote sensing data classification (1985–2019)	The spatial extent of ecosystems and LU changes	All ecosystems
Fragmentation of Ecosystems	a) Ecosystem extent assessment b) computation of P_f and P_{ff}		P_f and P_{ff}	Forests
Carbon sequestration potential	i). Quantification of AGB (above-ground biomass), and BGB (below-ground biomass) through field measurements using transect cum quadrat; ii). Carbon estimation from (AGB, BGB), and soil organic matter (SOC); iii). Literature review related to sequestration of carbon from forest, soil	Field Data & Carbon Sequestration; Data (training data – corresponding to various land uses and vegetation types) were collected across districts from August 2019 to February 2020 using a pre-calibrated handheld global positioning system (GPS).	Carbon Sequestration	Karnataka - district wise Carbon sequestrations in ecosystems - Forests, agriculture, plantations, soil
Biotic Elements Flora, Fauna, Conservation Reserves	Transect-based quadrat method for mapping flora and fauna	Field investigations & Data from the Karnataka Biodiversity Board (KBB)	Threat status – as per IUCN and KBB	All districts – forests
Geo-climatic Altitude, (Elevation), Slope, Rainfall	Elevation profile derived from Cartosat DEM of 1 arc second resolution; Point-based daily rainfall data from various rain gauge stations in and around the study area between 1901 and 2010 were considered for analysis of rainfall. The latest rainfall data has been obtained from WorldClim - Global Climate Data.	Daily rainfall details were collected from the Directorate of Economics and Statistics (DES), Government of Karnataka; Indian Metrological Department (IMD), Government of India.	Elevation, slope, rainfall – assigned ranks based on the relative weights	All Districts
Renewable Energy – Solar, Wind, Bio	Interpolation based on the data from NOAA Bioresources – field investigation with LU analyses	NOAA, Field data		Karnataka State- district wise
Social aspects, Population density, distribution of the tribal population (forest-dwelling communities)	Computation of Population density, the spatial distribution of tribal population	Data from Karnataka Remote Sensing Application Centre and Directorate of Economics and Statistics, Karnataka (2011, 2021a ,b)	Population density	Karnataka – all districts
Prioritization of grids	Based on the aggregated score/composite metric	Aggregated score computed based on an overlay of all themes	As per the mean (μ) and standard deviation (σ) of the composite metric	At the panchayat level for the entire Karnataka State, India

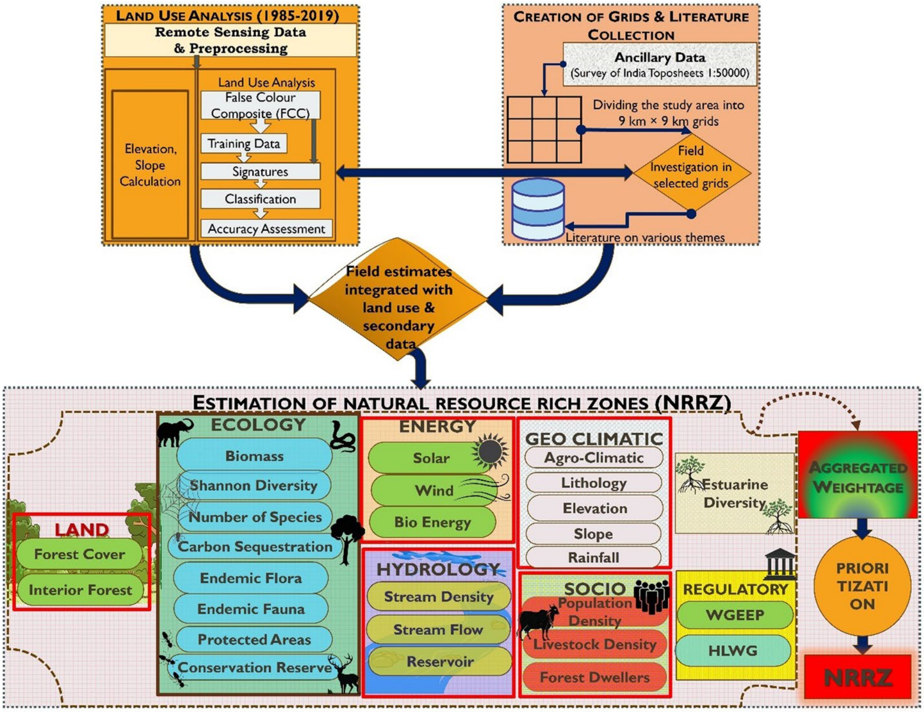

Fig. 2 Method used for NRRZ prioritization

Forest fragmentation analysis Land use data has been used to assess ecosystem conditions through the fragmentation of forests. Forest fragmentation analysis of Karnataka is assessed through computation of P_f (Eq. 1), and P_{ff} indicators (Eq. 2) carried out using 5×5 kernel at the pixel level (Riitters et al. 2000; Ramachandra et al., 2016, 2024). P_{ff} estimates the conditional probability that given a pixel of a forest, its neighbor is also a forest based on the proportion of all adjacent (cardinal directions only) pixel pairs. The temporal land use information is the input for the fragmentation model by reclassifying forest and non-forest categories. P_f and P_{ff} indicators aided in assessing various kinds of fragmentation. Natural features such as water bodies, rivers, and streams were considered as non-fragmenting landscape features. In contrast, anthropogenic features such as buildings, linear infrastructure, croplands, and barren areas were considered as factors inducing fragmentation.

$$P_f = \frac{Proportion\ of\ forest\ pixels}{Total\ non-waterpixels\ in\ window} \tag{1}$$

$$P_{ff} = \frac{Proportion\ of\ forest\ pixel\ pairs}{Total\ adjacent\ pairs\ of\ atleast\ one\ forest\ pixel} \tag{2}$$

2.3.2 Grid creation, field investigation and literature compilation

The study region (Karnataka State) is divided into grids (9 km x 9 km), which also overlap with the spatial extent of a panchayat, which is the administrative unit for decentralized governance as per the Panchayati Raj Act, GoI (The Constitution: Seventy-Third Amendment Act, 1992, Government of India) and management of biodiversity through Biodiversity Management Committee (BMC) as per the Biodiversity Act, 2002, Government of India. The Survey of India (SOI) topographic maps of 1:50000 (http://www.thesurveyofindia.gov.in) have been considered a reference for creating grids to generate base layers of the boundary. The grid-level analyses help account for micro-level changes, which is the optimal sample size (which defines the sampling intensity) for recording the data on different inventory parameters. The review of the literature included of themes of land (forest cover and status), geo-climatic (agro-climatic zones, altitude, slope, soil, lithology, rainfall), ecological (biomass, carbon sequestration, Shannon Diversity; endemic flora, endemic fauna, conservation reserves, bioresource status and the number of species), renewable energy prospects (solar, wind, bio), social (population & livestock densities, forest-dwelling communities), estuarine diversity and earlier regulatory instruments (WGEEP- the Western Ghats Ecology Expert Panel; HLWG- High-Level Working Group). Biomass and carbon estimation was done through field investigations in the representative grids of agro-climatic zones and landscape elements. The field investigation was carried out in the select district grids to collect data related to ecology, biodiversity, carbon stock, and to assess the hydrologic regime, which was further integrated in the analyses. The biomass (above-ground biomass) is estimated with field measurements and the information compiled from the literature (Kaul et al., 2010; Lal, 2004; Ramachandra et al., 2010; Rao et al., 2013; Ramachandra & Bharath, 2019). The field estimations were across representative forest types covering 424 transects in Uttara Kannada, Shimoga, Chikmagalur, Kodagu, Dakshina Kannada, Udupi, Dharwad, etc. The number of quadrats per transect varied between 3 and 5 depending on species occurrence (species-area curve) in the sampling locality. The biomass was estimated by measuring GBH (girth at breast height ot at 130 cm) and height of trees (>30 cm girth) in 20×20 m quadrats and shrubs (<30 cm girth) in 5×5 m quadrats and grass in 1×1 m quadrat as shown in Fig. 3. The transect data with data from published literature were used for biomass quantification. The basal area, height, vegetation type (evergreen, deciduous, semi-evergreen, moist deciduous, scrub forests), diversity, biomass, carbon stock, etc. were computed based on the compiled data across forest types in the state.

Tree species diversity was calculated through Shannon's diversity index (H') as per Eq. 3, which accounts both abundance and evenness (Magurran, 1988; Brose et al., 2003) and considers all species according to their frequencies (Lou, 2006).

$$Shannon's\ divesity\ index\ (H)' = -\sum_{i=1}^{n} (pi)\,\mathrm{lnpi} \quad (3)$$

where pi is the proportion of the species relative to the total number of species, and Shannon's diversity ranges from 1.5 to 3.5. So, a higher diversity is assigned a higher weight.

Endemic flora and fauna details were compiled from the field and supplemented with the review of published literature and virtual data portals (Karnataka Biodiversity Board, Karnataka Forest Department).

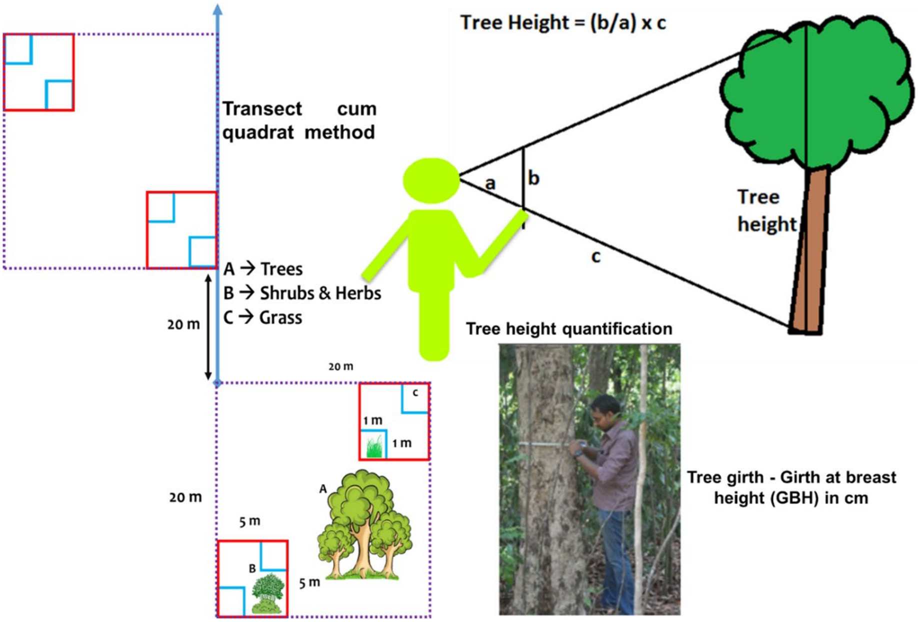

Fig. 3 Field measurement for vegetation survey

2.3.3 Data integration and prioritization of NRRZs

The process of identifying NRRZ (ESR) involved 4 steps: (i) identifying the significant factors that elucidate the natural resources (with the ecological and environmental) status (Zhang & Xu, 2017; Liu et al., 2015); (ii) assigning weights based on the extent and condition and generating thematic spatial layers based on the environmental weights; (iii) generating aggregated weight per grid 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 composite (aggregated weight) metric score considering various themes (Eq. 4) is computed for each grid. Developing a weight-based metric score by integrating diverse information (Termorshuizen & Opdam, 2009) aids in planning through visualization of the present and future landscape needs (Ramachandra et al., 2017, 2018). The novelty of the current study is prioritization of NRRZ at disaggregated levels grids of 5' x 5' (or 9 km x 9 km, equivalent to a grid in 1:50000 topographic map of the Survey of India) and also the decentralized governance unit- Panchayat (https://secforuts.mha.gov.in/73rd-amendment-of-panchayati-raj-in-india/) through the integration of diverse multi-dimensional bio-geo-climatic, environmental and social factors.

The current approach is significantly superior to traditional conservation planning approaches, which operate at coarser resolutions with a single theme that often remains disconnected from implementation realities. The integration of scientific rigor with administrative pragmatism offers a valuable model for evidence-based environmental management in complex socio-ecological systems. The NRRZ procedure's strength is the replicability for real-world conservation governance and prudent management of natural resources. The approach provides an objective and transparent system for combining multiple data sets to infer the significance (Beinat, 1997) and helps in prioritizing natural resources-rich (or eco-sensitive) regions based on composite weights as per Eqs. 4,

$$Weight = \sum {}_{i=1}^{n} W_i V_i \tag{4}$$

where n is the number of data sets, V_i is the value of the chosen variable for criterion i, and Wi is the weight. Wi is normalized between 10 (high priority) to 2 (least), and weights of 8, 6, and 4 correspond to high, moderate, low levels of protection/management (Table 2). Weights computed for each variable are aggregated for each grid, and grids are grouped into NRRZ 1, NRRZ 2, NRRZ 3, and NRRZ 4 based on the aggregated scores.

NRR Zone 1 consists of the most natural resource-rich (ecologically sensitive) grids, and NRR Zone 4 is the least resource-available grid (least ecologically sensitive). The aggregated score is considered for each district, and gradation has been done under two strategies: Western Ghats districts and others (non-Western Ghats districts). For the allocation of the NRR zones, corresponding to the Western Ghats districts, NRR zones 1 covers the value $> \mu + 2\sigma$, NRR 2 (grids within $\mu + 2\sigma$ and $\mu + \sigma$), NRR 3 (for grids with $\mu + \sigma$ and μ) and NRR 4 (grids with values $< \mu$) for grids in the Western Ghats region and a similar approach is adopted for non-Western Ghats grids and details are listed in Table 3 for the districts which lie in the Western Ghats and also for non-Western Ghats districts. Here, μ is the mean of the composite metric score, and σ is the standard deviation. The results provide a micro-level granularity for decision-making and aid in capturing the heterogeneity, which enables precise targeting of conservation interventions.

3 Results

NRRZs in Karnataka state are identified and prioritized through composite metrics considering land use, geo-climatic, ecological, energy, and social variables at disaggregated levels (grids). The NRRZ depicts the resource status and their sensitiveness in supporting people's livelihood through the sustenance of goods and services of ecosystems. The theme-wise data and their significance are discussed next.

3.1 Land

The analyses of LU dynamics in Karnataka State indicate the loss of forest cover (15% in 2019 compared to 21% in 1985) with an increase in built-up area. Land use of 2019 is used for assigning weights. The grids of Western Ghats districts have higher forest cover than other districts, as depicted in Fig. 4. The extent of the forest is considered for prioritizing NRRZ at disaggregated levels and is in the existing restricted areas, protected under

Table 2 Allocation of weights across the themes

SNO	Theme	Variable	Weight				
			2	4	6	8	10
1	**Land**	Forest Cover	< 15%	15–30%	30–45%	45–60%	> 60%
		Interior Forest Cover	< 15%	15–30%	30–45%	45–60%	> 60%
2	**Biotic - Ecology**	Flora	Non-endemic	–			Endemic/ Threatened flora
		Fauna	Non-endemic	–			Endemic/ Threatened fauna
		Protected Area (PA)	Wi = 0 for grids exterior of PA				10 was assigned to the grids within PA
		Mysore Elephant Conservation Reserve (MECR)	Wi = 0 for grids exterior of MECR				10 was assigned to grids of MECR
		Shannon Diversity	< 1	1–1.5	1.5–2	2–2.5	> 2.5
		Species Number	< 50	50–100	100–150	150–200	> 200
		Biomass (Gg)	< 300	300–600	600–900	900–1200	> 1200
		Carbon Sequestration	< 300	300–600	600–900	900–1200	> 1200
3	**Geo- climatic**	Agro-Climatic Zone	Karnataka Plateau, Arid	Karnataka Plateau, Semi-Arid	Karnataka Plateau, Hot Moist Semi-Arid	Coastal Hot Humid	Western Ghats Moist Sub Humid
		Altitude	–	< 250 m	250–500 m	500–750 m	> 750 m
		Slope (%)	–	–	–	> 15	> 30
		Rainfall	< 600 mm	600–1200	1200–1800	1800–2400	> 2400 mm
		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
4	**Hydrology**	Stream Density	< 1	1–1.5	1.5–2	2–2.5	> 2.5
		Stream Frequency	< 1.25	1.25–2.5	2.5–3.75	3.75–5	> 5
		Reservoirs	–	–	–	Exists	–

Table 2 (continued)

SNO	Theme	Variable	Weight				
			2	4	6	8	10
5	**Energy**	Solar	–	–	–	< 6 KW/h	> 6 KW/h
		Wind	1.5	1.5–2	2–2.5	2.5–4	> 4 m/second
		Bio	–	230,000	230,000–360,000	360,000–660,000	> 660,000
6	**Estuaries**	Diversity	–	–	–	Moderate	Rich Diversity
7	**Social**	Population Density	> 1000	500–1000	250–500	100–250	< 100 (persons per ha)
		Livestock Density	< 0.75	0.75–1.5	1.5–2.25	2.25–3	> 3 animals per ha
		Forest Dwellers	–	–	Tribal population in non-forest cover grids	Tribal population in the least forest cover grids	Presence of tribal population in forest grids
8	**Regulatory Framework**	The Western Ghats Ecology Experts Panel (WGEEP)	–	–	–	–	ESR-1 mapped by WGEEP
		HLWG (High-Level Working Group	–	–	–	–	ESA-1 mapped by HLWG

Table 3 Allocation of NRR zones

Karnataka Districts	NRRZ 1	NRRZ 2	NRRZ 3	NRRZ 4
Under Western Ghats (i.e., Uttara Kannada; Udupi; Dakshina Kannada; Kodagu; Belgaum; Shimoga; Chikmagaluru; Hassan; Mysore; Chamarajanagara; Dharwad; Haveri)	$> \mu+2\sigma$	$\mu+2\sigma$ and $\mu+\sigma$	$\mu+\sigma$ and μ	μ and $> \mu-\sigma$
Others (non-Western Ghats)	$> \mu+\sigma$	$\mu+\sigma$ and μ	μ and $> \mu-\sigma$	$\mu-\sigma$ and $> \mu-2\sigma$

μ: mean (of aggregated values of weight), σ: standard deviation

regulatory framework (national parks, tiger reserves, wildlife sanctuaries, etc.). During the post-globalization era, forests and agricultural land experienced a decline, with the spurt in urbanization and infrastructure with industrialization.

The forest ecosystem condition is assessed through fragmentation analysis, which reveals the decline of interior or intact forests over a temporal scale. The contiguous intact (or interior) forests in the state have declined (Fig. 5) from 16.3% (1985) to 6% (2019), with

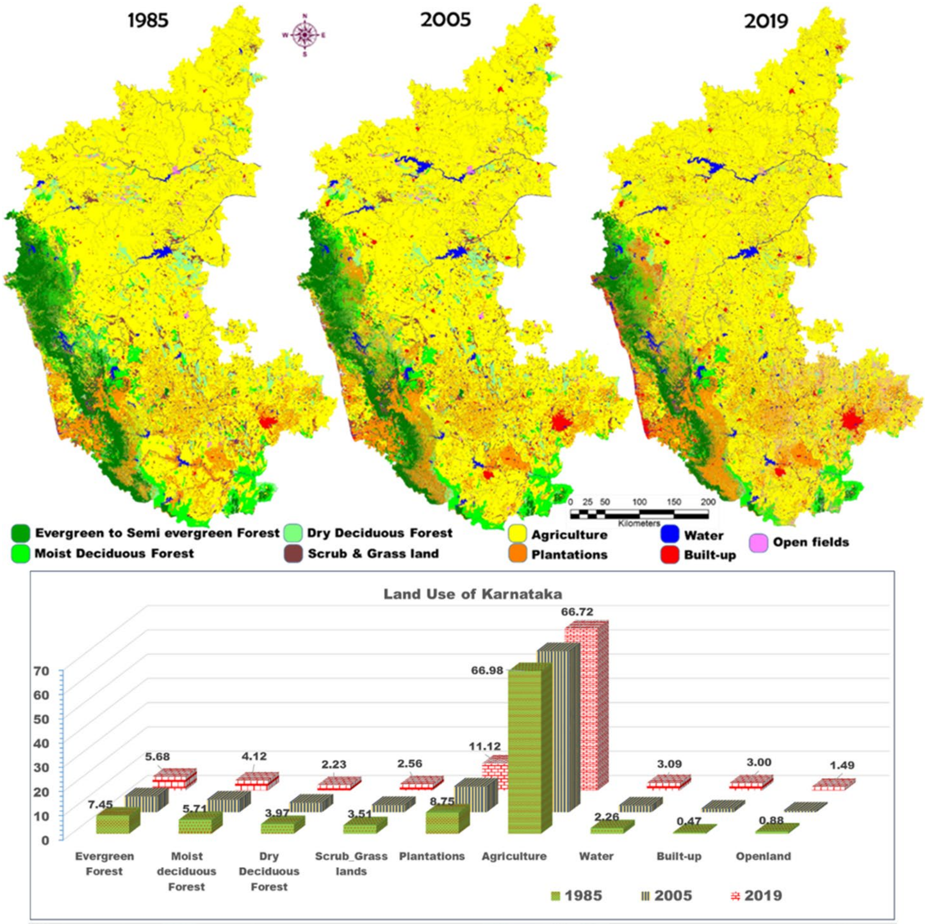

Fig. 4 Spatiotemporal LU changes in Karnataka

an increase in non-forest cover from 74 to 85%. The fragmentation of forests is evident with the increase in the number of patches, perforated forest cover, etc., with the conversion of forests to built-up, construction of linear corridors (road, rail network), and construction of reservoirs, dams (Ramachandra et al., 2021). Intact forests in Uttara Kannada, Dakshina Kannada, Kodagu, Udupi, and Shimoga districts are now confined to valleys, mountainous regions, and sacred grooves.

Figure 6 depicts the extent of forests across grids in Karnataka. The forest cover of > 60% is in grids of Western Ghats districts (Uttara Kannada, Belgaum, Shimoga, Chikmagalur, Kodagu, Udupi, Dakshina Kannada, Chamarajanagara, etc.). The northern Karnataka districts have a < 10% to 0 forest cover. Grid-wise weights are computed based on the weights and extent of forest cover with weights of 10) for the regions of higher forest cover, and the least weight is assigned to grids with less forest cover.

Fragmentation of forests results from the sustained anthropogenic pressure, resulting in the degradation of forests with patches, etc. The interior forest (intact) cover is confined to

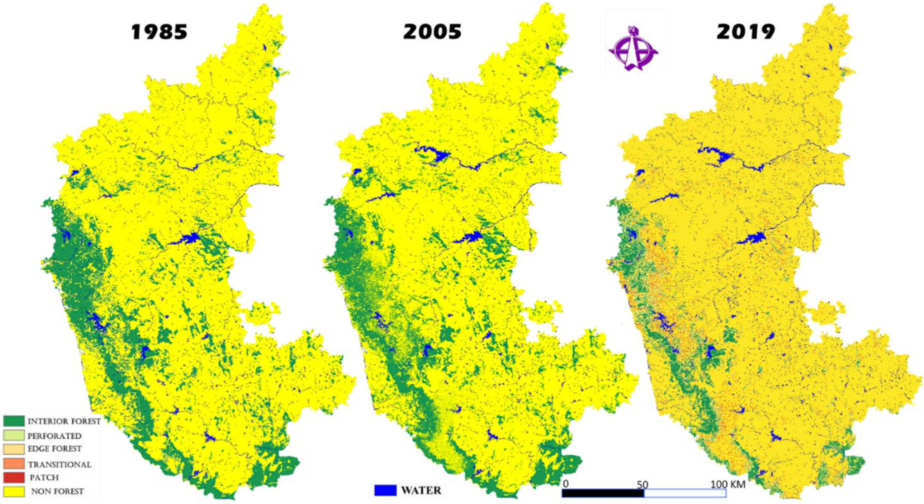

Fig. 5 Fragmentation of forests from 1985 to 2019

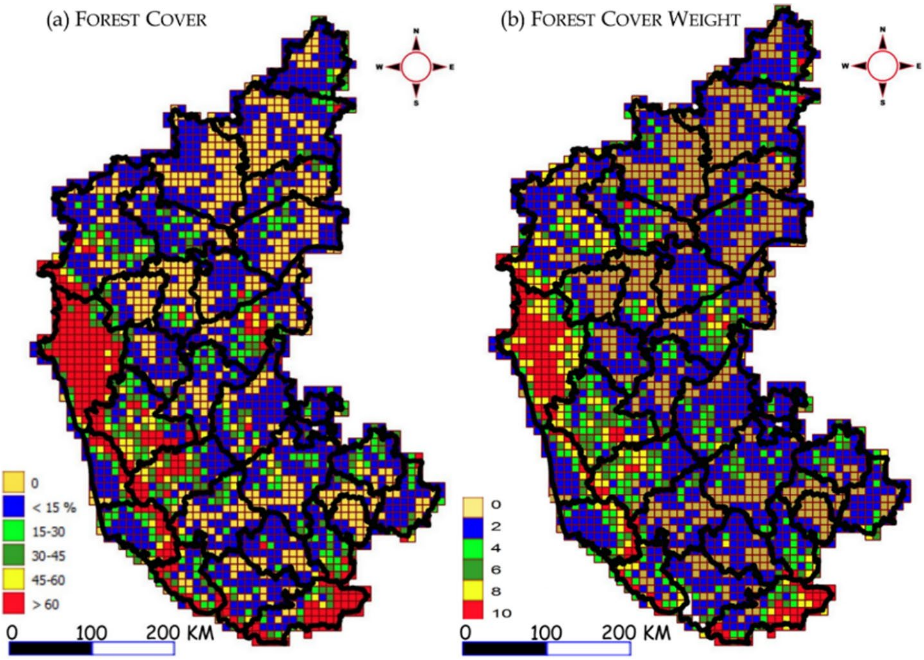

Fig. 6 Forest cover (across grids) in Karnataka with weights

protected areas such as National Parks (NP), Wildlife Sanctuaries (WLS), and Reserves. Bellary, Mysore, and Chamarajanagara districts have lost major tracts of interior forest cover. Weights are assigned as listed in Table 2, and Fig. 7 depicts the grid-wise condition of forests based on the level of fragmentation with relative weights.

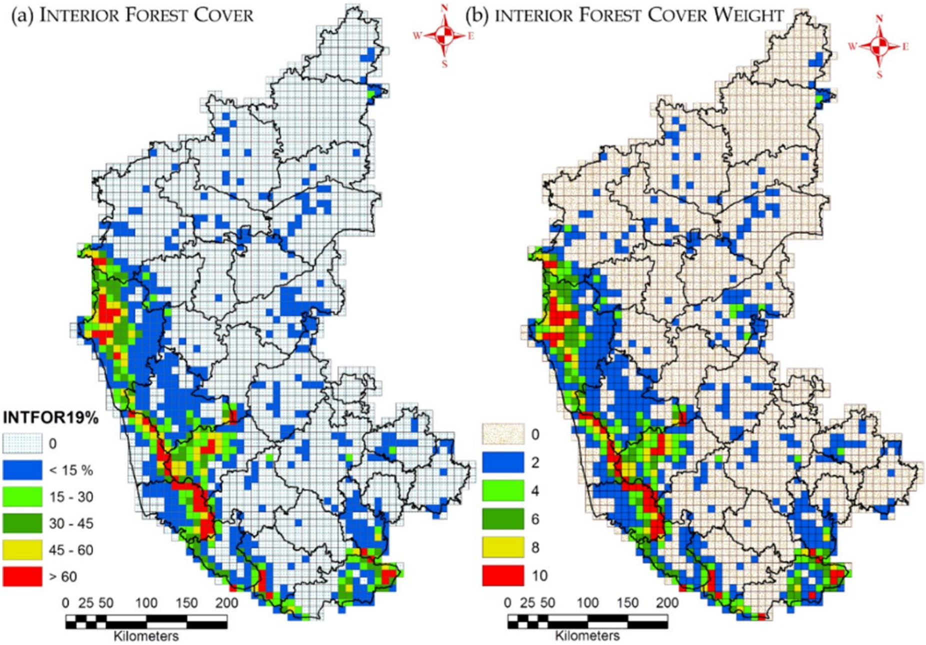

Fig. 7 Interior forest cover in Karnataka with weights (across grids)

3.2 Ecology

The ecology is assessed through variables such as biomass, species diversity, species distribution, endemic taxa, conservation reserves, etc.

3.2.1 Carbon

The standing biomass or above-ground biomass (AGB) and below-ground biomass (BGB) were estimated as per the standard protocol (Murali et al., 2005; Ravindranath & Ostwald, 2008; Ramachandra & Bharath, 2021). The total AGB of Karnataka forests is about 733 Tg (Teragram), and BGB is 181 Tg, respectively (2019), and the spatial variation of biomass in the state is given in Fig. 8. The grids corresponding to evergreen forests in the Western Ghats have higher AGB > 1000 Giga gram (Gg) and hence assigned a higher weight.

Carbon in forests is quantified by multiplying total (AGB + BGB) biomass by 0.5, and the assessment shows that carbon sequestered in forest ecosystems of Karnataka accounts for 457 Tg. The grids of Uttara Kannada, Kodagu, Shimoga, Udupi, and Chikmagalur districts, with a relatively high forest cover, have higher carbon levels than other districts (Fig. 9).

3.2.2 Biodiversity

Shannon diversity of plants per grid is computed as per Eq. 4. Compared to other parts of the state, the grids of Western Ghats districts have higher diversity (greater than 2) (Fig. 10). The grids of Bidar, Mandya, and Vijayapura districts have lower diversity, and weight was

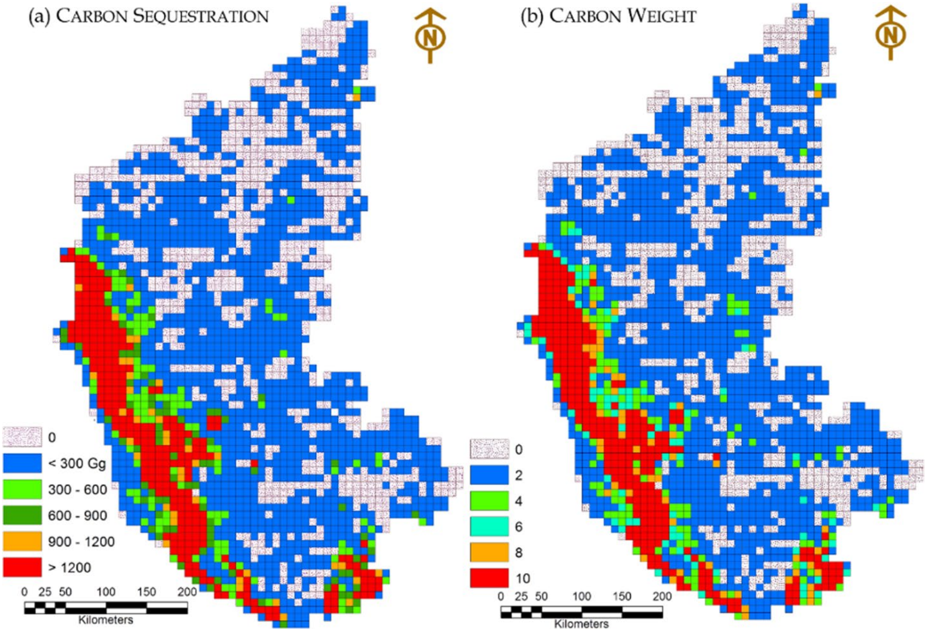

Fig. 8 Carbon sequestration in forests of Karnataka with weights (across grids)

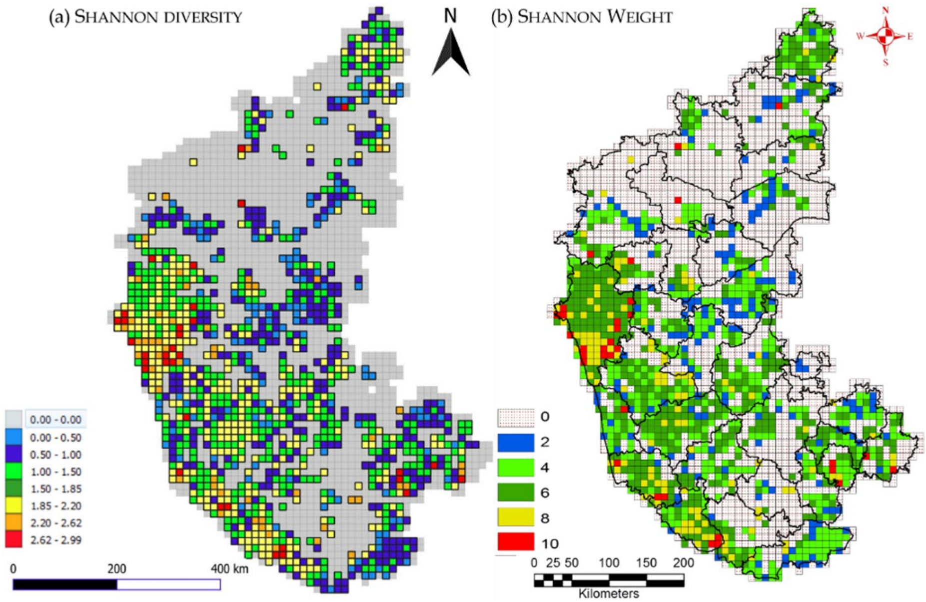

Fig. 9 Shannon diversity with weights (across grids)

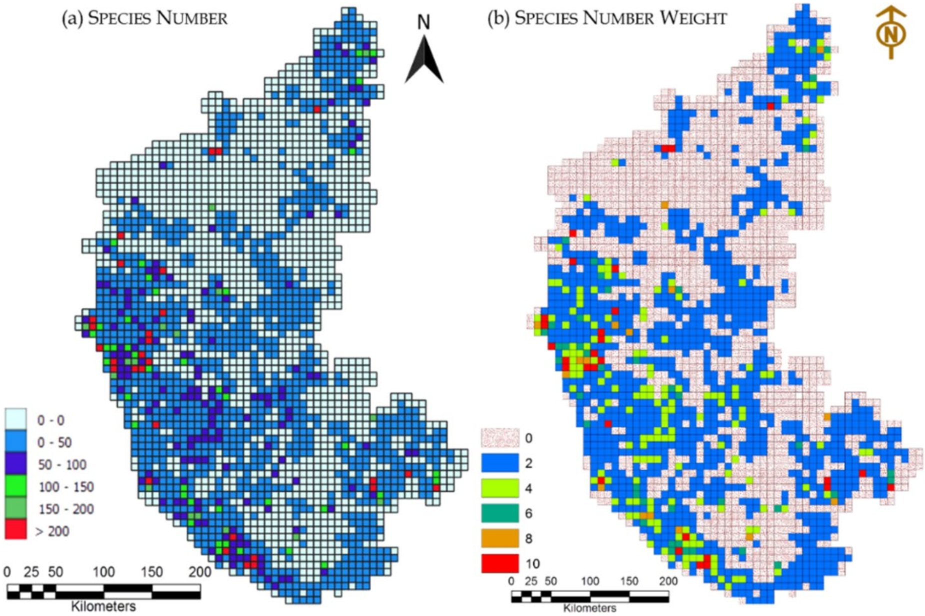

Fig. 10 Species distribution (abundance) with weights (across grids)

computed accordingly. The number of species per grid is assessed to account for the diversity and number of unique plant species in a grid. Figure 11 depicts that Uttara Kannada, Dakshina Kannada, and Kodagu district grids are endowed with a higher number of species, and weights are assigned accordingly.

Karnataka has 5164 plant species (294 families), and the most abundant species are *Mangifera indica*, *Cassia fistula*, *Azadirachta indica*, *Ficus racemosa*, and *F.religiosa* (; Ramachandra et al., 2024). Fabaceae, and Poaceae are the most dominant families. Endemic flora details are compiled through field investigations and supplemented with details from published literature and data portals (Karnataka Forest Department, Karnataka Biodiversity Board;; Ramachandra et al., 2024). The grids containing prime endemic flora such as *Hemidesmus indicus*, *Erythrina indica (variegata)*, *Flacourtia montana*, *Garcinia gummi_gutta (cambogia)*, *Holigarna grahamii*, *Hopea ponga*, *Knema attenuata*, *Saraca asoca*, *Syzygium mundagam*, etc. were assigned weight of 10 and Fig. 12 depicts the distribution.

Fauna of the State covers birds (812 species), fishes (428), Mammals (249), amphibians (165), reptiles (247) and butterflies (438), etc. The endemic fauna (assigned weight 10) includes *Macaca silenus*, *Vandeleuria nilagirica*, *Viverra civettina*, *Fejervarya nilagirica*, *Indirana beddomii*, *Indirana gundia*, *Nasikabatrachus sahyadrensis*, *Turdoides subrufa*, *Garra bicornuta*, *Puntius cauveriensis*, *Tor mussullah*, *Mabuya beddomii*, *Trimeresurus malabaricus* etc. Figure 13 depicts the grid-wise spatial distribution of endemic fauna, indicating the highest in Uttara Kannada and the lowest in Koppal and Raichur districts.

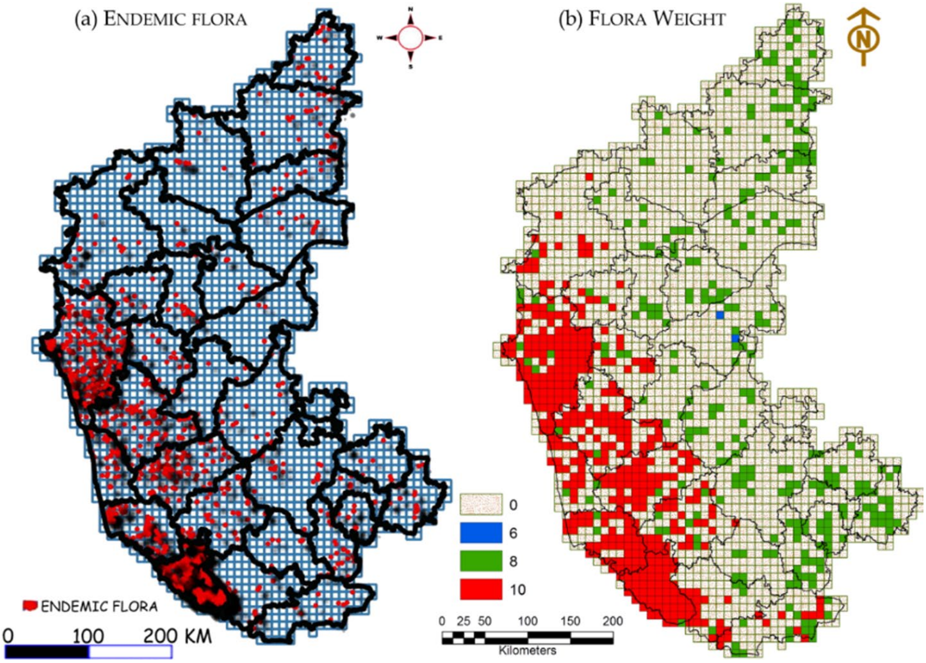

Fig. 11 Endemic flora distribution with weights (across grids)

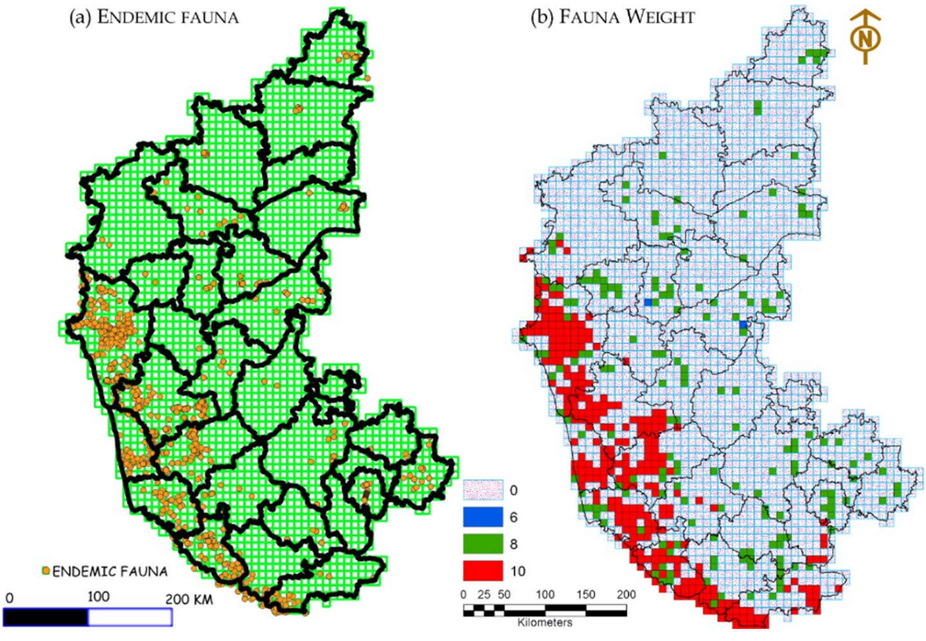

Fig. 12 Endemic fauna distribution with weights (across grids)

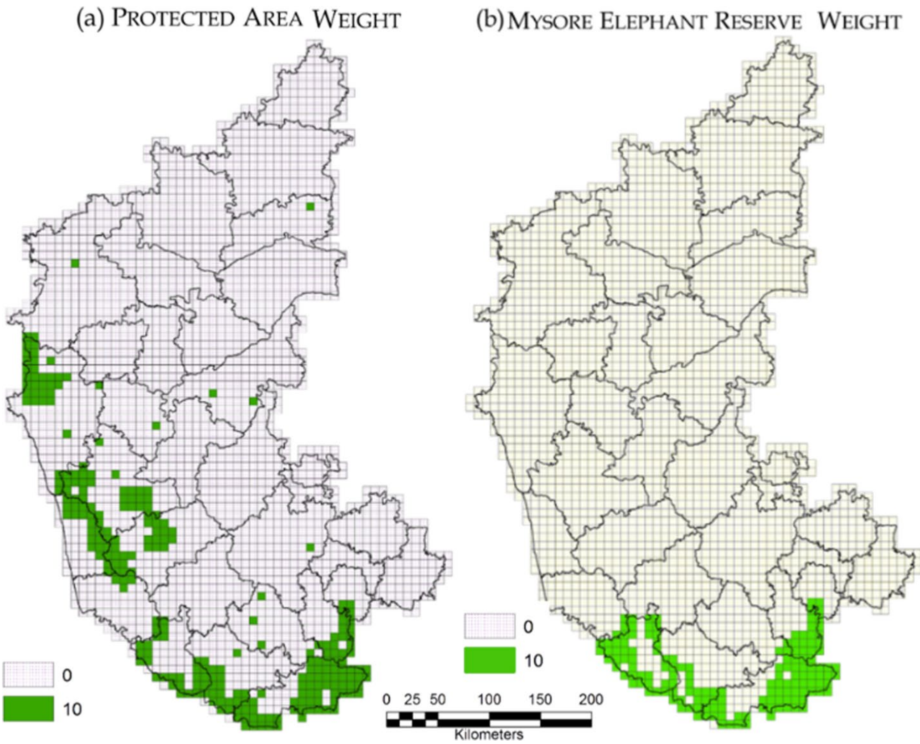

Fig. 13 Protected Areas of Karnataka and Mysore Elephant Reserve with weights (across grids)

3.2.3 Protected area

Globally, establishing protected areas (PA) is a measure of conservation. According to the International Union for the Conservation of Nature (IUCN), nearly 15.2% of the global land surface is now under some form of protection. Protected Areas such as National Parks (NP), Wildlife Sanctuaries (WLS), and Bio-Reserves notified under the section of the Wildlife Protection Act (WPA), 1972 (amended up to 2003) are mapped and a weight of 10 is assigned to the grids of PAs as these regions are already prioritized for preservation and conservation.

Mysore Elephant Conservation Reserve is a critical habitat with a rich resource base (fodder, water, etc.) and elephant movement corridors. Karnataka has a primary elephant corridor connecting northern and southern portions as a Mysore elephant reserve (Fig. 13). Mysore Elephant Reserve is spread across 6,463 km^2 connects Kerala, Karnataka, and Tamilnadu state forests, and has 6072 elephants as per the elephant census (Baskaran et al., 2011). Human-elephant conflicts are widely reported at locations prone to fragmentation of habitats with discontinuity and disturbances. The grids corresponding to Mysore Elephant Reserve are mapped and assigned a weight of 10 for the conservation of umbrella species.

3.3 Geo-Climate

Geo-climate data of varied spatial resolutions aid in spatial analyses, which form the basis for scientific conclusions, management decisions, and other vital outcomes. Geo-climatic variables such as altitude (elevation), slope, and rainfall significantly influence local ecology and socio-economic interactions (Wondie et al., 2012). The elevation and slope maps are generated using the Cartosat DEM data set. Areas with steep slopes and high altitudes are likely to be eroded more easily, and hence vulnerable to natural erosion or landslides, which further impacts natural resources. The slope map is generated from DEM data set. The rate of change (delta) of the surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the center cell determines the slope. Slope values are (measured in degrees) extracted (Eq. 3) using slope the algorithm (Burrough, 1998) as,

$$Slope\ degrees = ATAN\left(\left(\left[\frac{dz}{dx}\right]^2\right) + \left(\left[\frac{dz}{dy}\right]^2\right)\right) \times 57.296 \qquad (5)$$

Where, dz/dx is the rate of change in the x direction; dz/dy is the rate of change in the y direction. Agro-climatic zones are geographical spaces of homogeneous weather conditions that significantly influence crop growth and yield. Understanding agro-climatic zones assists in assessing resources, determining appropriate localities for new crop production technologies (Araya et al., 2010), and examining the effects of climate change on agriculture (Fischer et al., 2005). Weight is assigned to grids based on climatic conditions, as shown in Fig. 14.

The elevation plays a role in the microclimate of a region and indirectly represents the gradient of resources and external pastures. The moderate elevations (valleys) and high-elevation regions are endowed with pristine forests based on climatic conditions. These regions are environmentally sensitive zones as they are the least resilient but rich in natural resources. The region consists of the tallest peaks, namely Mullayyana Giri (1,925 m), Baba Budan Giri (1,894 m), Kudremukh (1,895 m), and the Pushpagiri (1,908 m). Weights are assigned to grids (Fig. 15) based on elevations as 0 (lowest altitude) to 10 (high altitude).

The relationship of slope and elevation with LU changes is considered. Modification of slopes for developmental activities results in the escalation of natural hazards during extreme climatic events such as rainfall, etc. The weights were assigned as per slope gradients as shown in Fig. 16.

Soil is a prime natural resource which plays a crucial role in the sustainability of life. The data were compiled from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP) organization (https://www.nbsslup.in/) and the European Commission Soil Data Centre (ESDAC) (https://esdac.jrc.ec.europa.eu/DocumentsPublications*).* There are 14 major distinguishable soil types in Karnataka (Fig. 17). Loamy and clayey types are highly fertile, and the weight is assigned based on productiveness.

Lithology is a key feature in controlling the tectonics and geomorphology of the region, besides its effects on erosional features. It also determines the major geochemical activity of the region, making it difficult to isolate the effect of a climatic constraint, and weight has been assigned accordingly (Fig. 18). There are around ten variants in the lithological groups, and the dominant are Peninsular Gneiss and Dharwars.

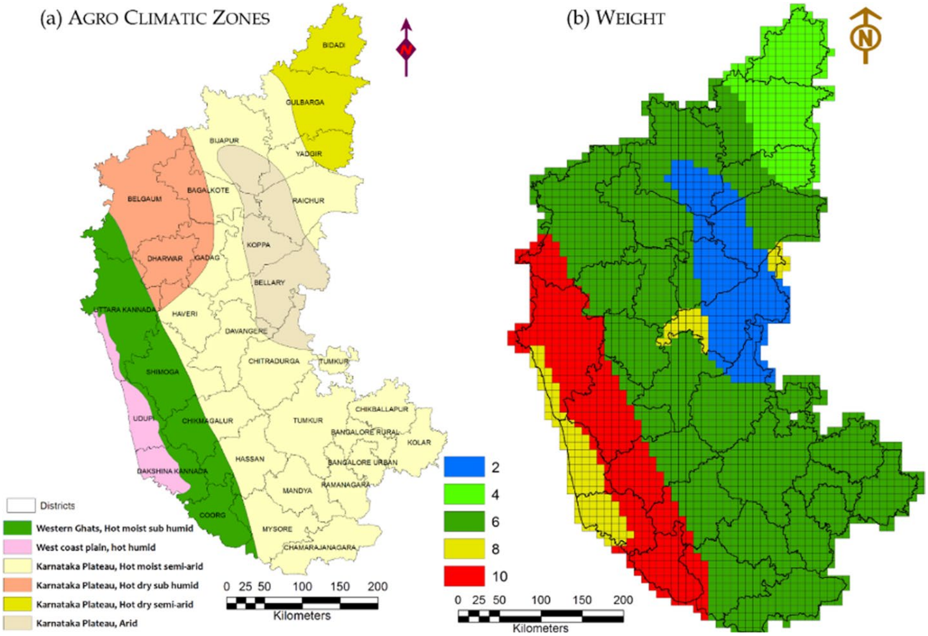

Fig. 14 Agro-climatic zones of Karnataka with weights (across grids)

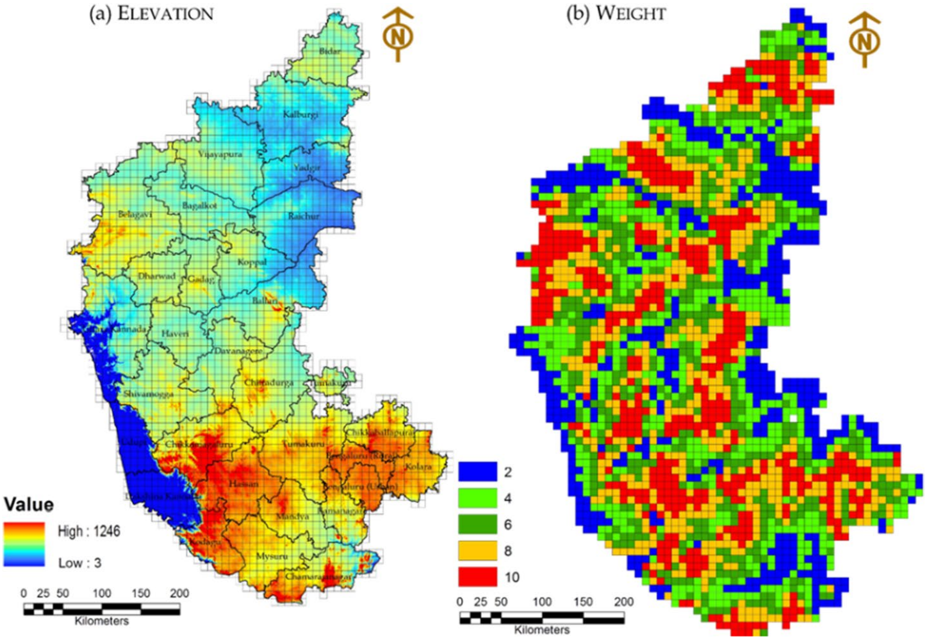

Fig. 15 Elevation of Karnataka with weights (across grids)

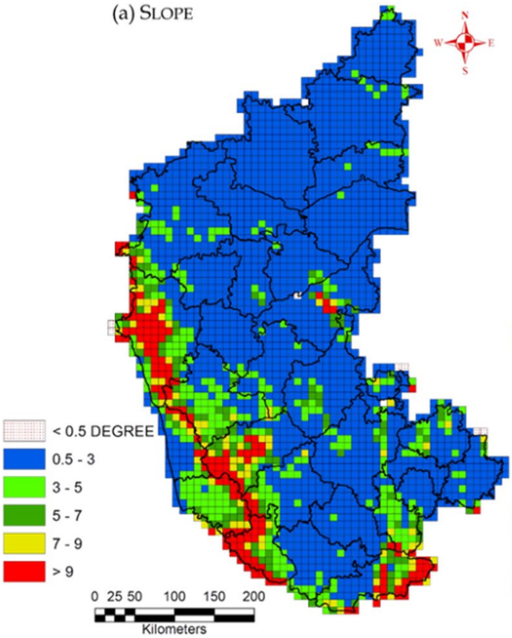

Fig. 16 Slope map of Karnataka with weights (across grids)

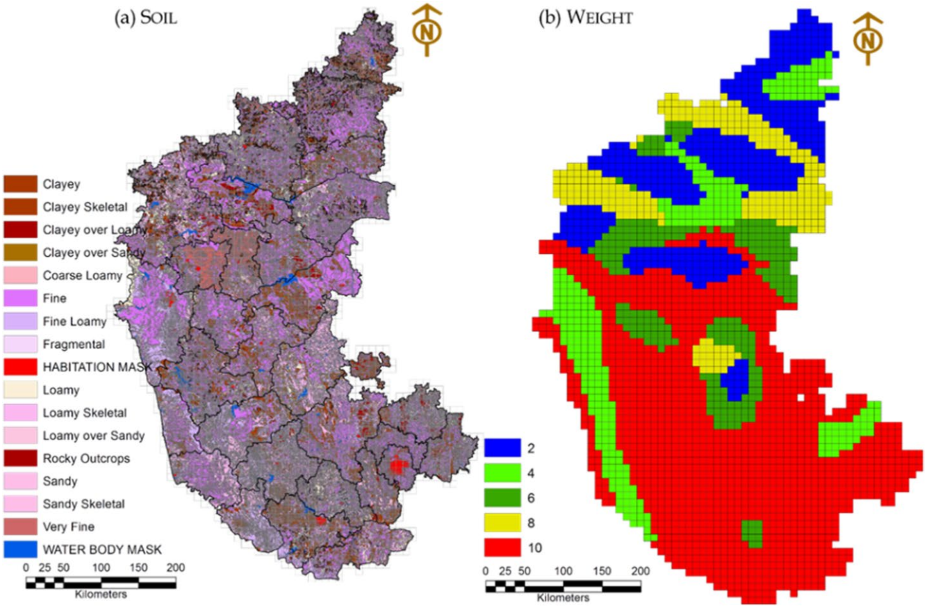

Fig. 17 Soil map of Karnataka with weights (across grids)

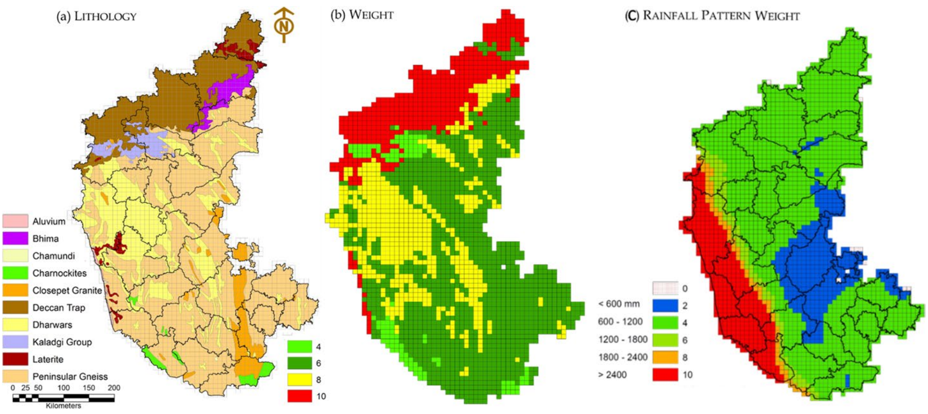

Fig. 18 Lithology and rainfall of Karnataka with weights (across grids)

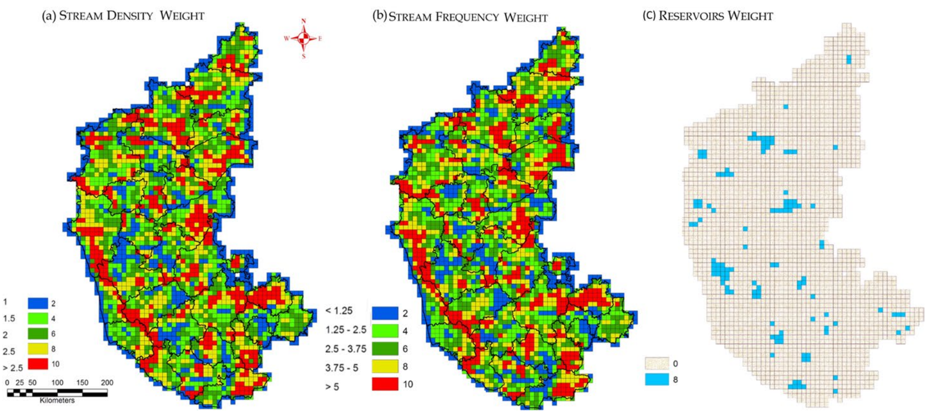

Fig. 19 Stream Density, Frequency, and Reservoirs of Karnataka with weights (across grids)

Rainfall data (1901–2010) and the latest rainfall data of WorldClim - Global Climate Data were analyzed to derive rainfall throughout the study area through the process of interpolation (isohyets). The state has an average rainfall of 1200 mm and receives rain in two monsoon seasons: North-East monsoon (October to December) and South-West monsoon (June to September), based on the rainfall pattern, and weights are assigned to grids (Fig. 18).

3.4 Hydrology

The hydrological assessment was carried out using stream density, stream frequency, and reservoirs. The stream network was delineated from topographical maps and DEM data. Based on the stream networks, stream density for every grid was calculated as the total length of streams per unit area. The weight is assigned as per density (Fig. 19). The range of values was then distributed into five categories, containing the highest values assigned a weight of 10 and the lowest set of values assigned a weight of 2.

Based on the stream networks, stream density was calculated grid-wise as the total length of streams per unit area, and the frequency was calculated based on the number of streams per grid.

The reservoirs with multi-functionalities support irrigation, hydroelectricity, recreation, navigation, and fisheries (Tundisi et al., 2008). Water bodies are part of the economic potential of a region, which supports quantitative economic activities such as domestic drinking, industries, farming, etc. The reservoir construction has advantageous social benefits but results in negative impacts such as the loss of biodiversity (aquatic and terrestrial) and the decline in water quality. A weight of 8 was assigned with respect to the reservoirs (Fig. 19).

3.5 Energy

Prospects of location-specific and decentralized energy resources such as solar, wind, and biomass have been analyzed to assess the renewable energy potential (Ramachandra & Shruthi, 2007).

Karnataka receives global solar radiation in the range of 5.1–6.4 kWh/m2 during summer, 3.5–5.3 kWh/m2 during monsoon, and 3.8–5.9 kWh/m2 during winter. The average solar radiation across grids is mapped, and weights are assigned to grids, as in Fig. 20.

The wind is a domestic source of energy that is reliable and cost-effective. It is a sustainable and clean fuel source, abundant and inexhaustible. Annual average wind speed data has been used for mapping wind potential zones across Karnataka, considering seasonal wind velocities at various locations season-wise as summer (February–May), monsoon (June–September), and winter (October–January). Belgaum has the highest wind velocity and the lowest wind velocity in Bagalkot.

Bioenergy is another form of solar energy generated through biomass. The organic matter derived from biological organisms (plants, animal residue, algae) is used for energy generation. The bioenergy potential of the state was evaluated by analyzing various organic matter availability, and weights were assigned based on the availability.

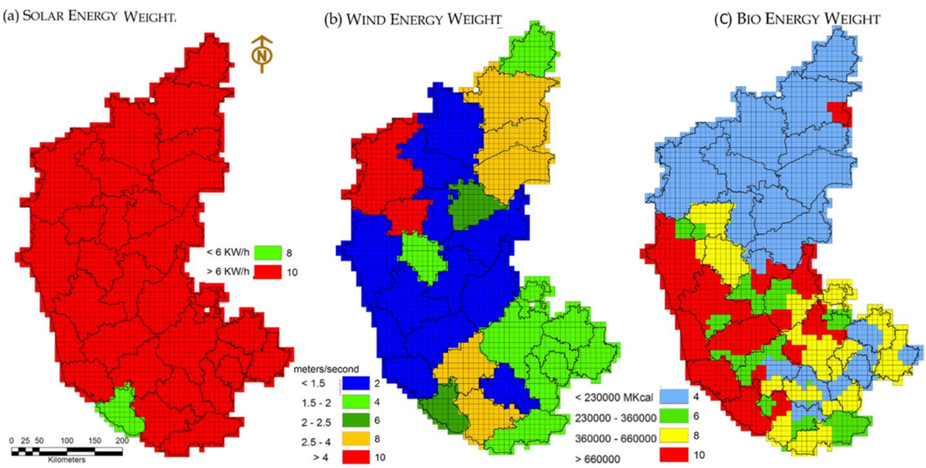

Fig. 20 Energy prospects of Karnataka with weights (across grids)

3.6 Social variables

Understanding the social systems and their interrelationship and interdependency on the natural environment at disaggregated levels provides an idea of impacts and responses on the various ecosystems. Hence, analyzing the social aspects would highlight the resource pressure and provide insights for planning and management.

The planners and natural resource managers have been accustomed to responding to values expressed by political and social systems derived from resource use and development (Kennedy & Thomas, 1995). Higher population density would increase stress on water and other natural resources, with decreased food security, slower development, and, consequently, aggravated poverty (Keskinen, 2008). The regions with a high population will have higher resource demand. A weight of 2 was assigned to high population density grids and 10 for the lower population density (Fig. 21).

The livestock or animal husbandry sector forms an important source of income for small landholders and landless households with employment, nutrition, and financial security. Livestock is a natural asset, and dependence of livestock products, such as milk, eggs, and meat, is increasing (Birthal et al., 2006). Agriculture and animal husbandry sector activities have contributed to 19% State's Gross State Domestic Product (GSDP). Animal husbandry activities support 5.5% of the state's workforce. The livestock density is mapped, and weight has been assigned. The higher density is seen in Belgaum, Davanagere, and Mandya districts.

Traditional forest dwellers (tribes) have been protecting forests since time immemorial, constitute genuine stakeholders, and enjoy the privileges as per the Forest Rights Act, 2006, GoI. This legislation empowers tribal communities with their traditional rights of forestland. They are recognized as a part of a cultural landscape linked to livelihood concerns of tradi-

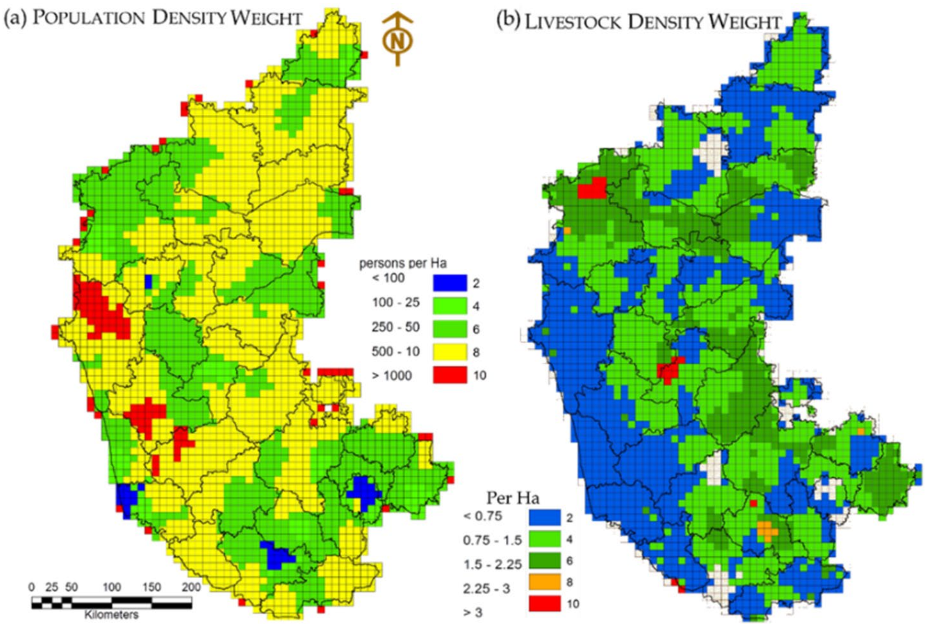

Fig. 21 Population, livestock densities with the relative weights (across grids)

tional societies, living close to nature with high natural resources. The state has 42,48,987 tribal people, and about 50,870 belong to the primitive group (Roy et al., 2015). Tribes constitute 6.95% of the state's population, with 50 tribal groups such as Soligas, Siddis, Kunabi, Jenu Kuruba, etc. Figure 22 gives the spatial distribution of the tribal population with weights.

3.7 Estuarine diversity

Estuaries are unique ecosystems that integrate geological, ecological, and biological domains supporting vast terrestrial and aquatic life. An estuarine zone is a land enclosed with water where rivers meet the Sea and aid as a breeding ground for numerous marine organisms (Mesta et al., 2014). The salinity of the region will be intermediary to that of marine and freshwater, where organic matter builds up in large quantities and offers ideal biotic conditions to sustain the considerable aquatic population. These regions provide a variety of ecosystem goods (fish, fodder, sand, salt) and services such as nutrient transfer, erosion control, and pollution control (Barbier et al., 2011; Anoop & Suryaprakash, 2008). The state has rich, diverse estuaries along the west coast with west-flowing rivers such as Kali, Aghanashini, Sharavathi, Netravathi, etc. The weight has been assigned depending on biodiversity, ecosystem goods, and services, as shown in Fig. 23.

3.8 Regulatory framework

The Ministry of Environment and Forests and Climate Change (MoEFCC) has taken many initiatives to protect the environment through the prevention and control of environmental

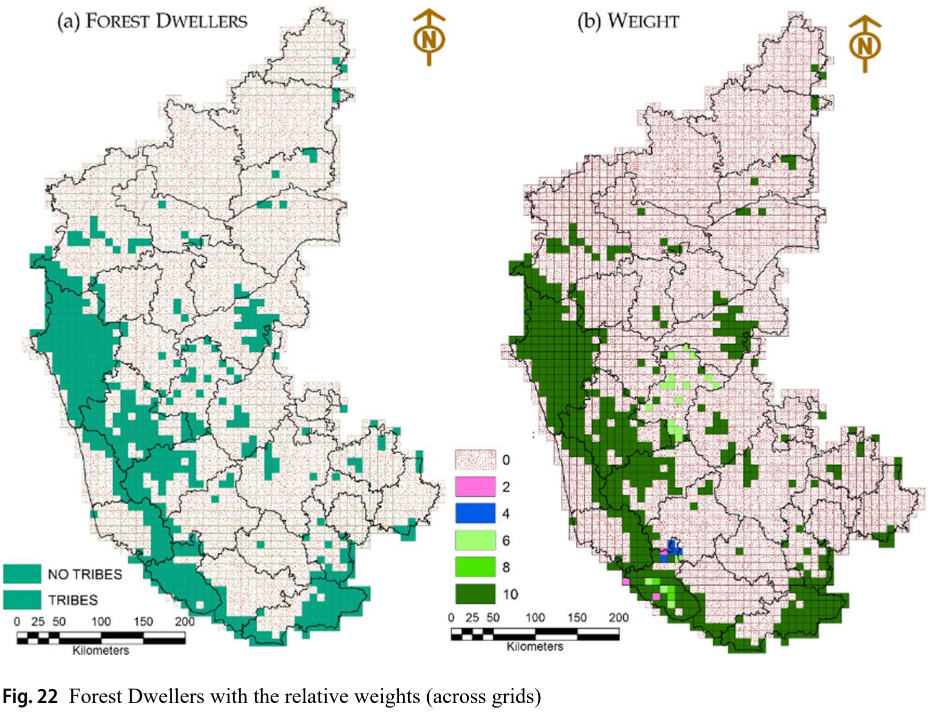

Fig. 22 Forest Dwellers with the relative weights (across grids)

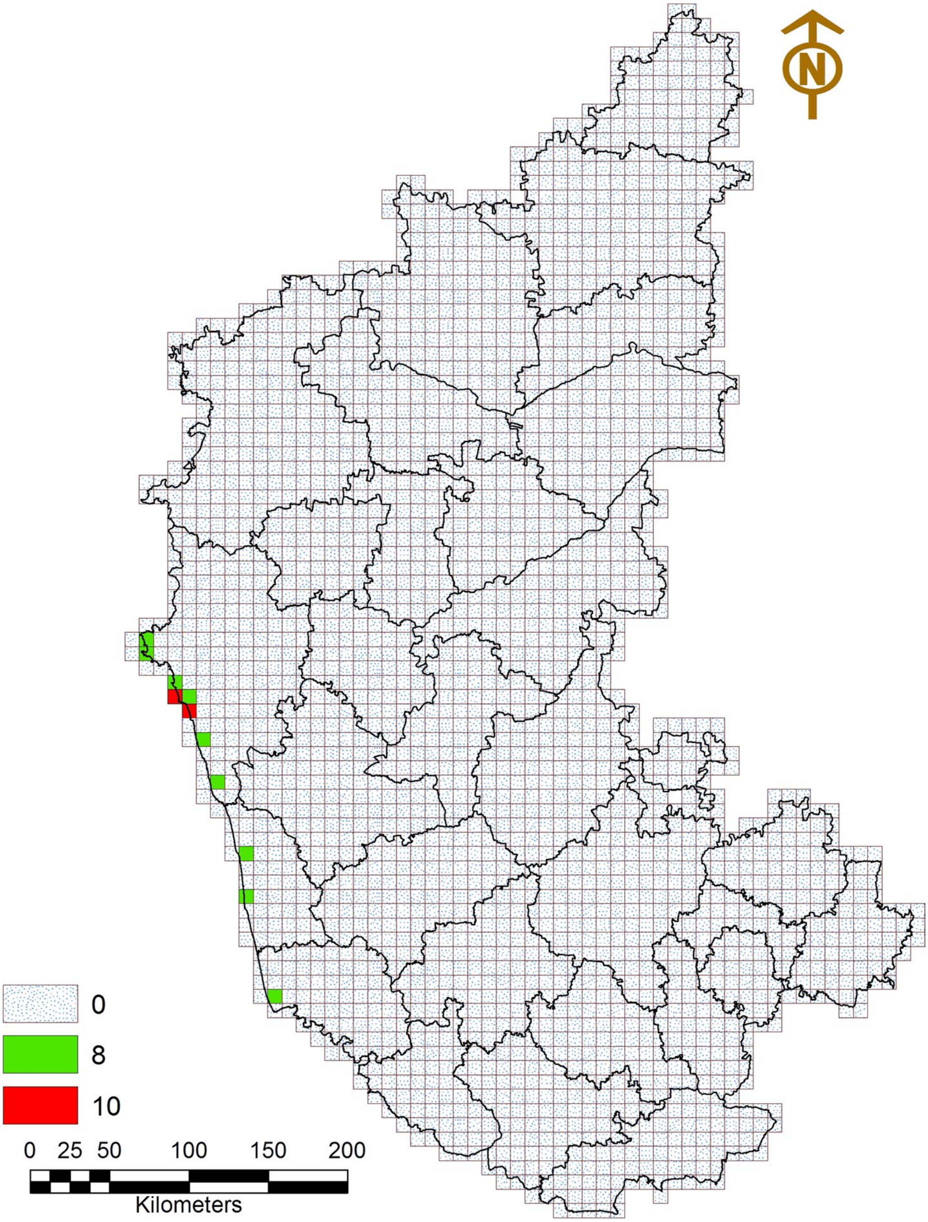

Fig. 23 Estuaries of Karnataka with weights (across grids)

pollution under Sect. 3 of the Environmental Protection Act 1986 (EPA). The Ministry has the legal capabilities to prohibit environmentally hazardous or polluting industries as per Sect. 5 of EPA. MoEFCC in 2000 constituted an expert committee (Pronab Sen committee: 2000) to provide guidelines to identify regions based on their ecological significance (MOEF, 2000). Subsequently, Western Ghats Ecology Experts Panel (WGEEP) was formed to suggest measures to arrest ecosystem degradations in the Western Ghats and formulate a protocol to delineate ecologically salient/sensitive zones (Gadgil et al., 2011). The committee recommended conserving ecologically 'salient' regions (ESR), based on the significance and local ecology (Fig. 24). Subsequently, High-Level Working Group (HLWG) based on geospatial analysis and high-resolution spatial datasets demarcated village-wise ESA (Ecologically Sensitive Areas) in the Western Ghats districts (Kasturirangan et al., 2013). However, the report failed to account for social dynamics, the role of ecology in sustainability, and the significance of biodiversity hotspot regions. This necessitated the integration of technologies coupled with multi-criteria analysis to delineate ecologically and economically significant conservation regions to sustain natural resources through appropriate conservation measures.

3.9 Prioritization of NRRZ at decentralized levels

Bio-geo-climatic, ecological, environmental, social, and conservation regions (as per WGEEP, HLWG) are aggregated (Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23 and 24) grid-wise, which are analyzed statistically to prioritize regions based on natural resources. The districts in the state are grouped as the Western Ghats and Non-Western Ghats districts for prioritization, as discussed in the method section. The natural resources-rich regions are prioritized and grouped into four categories based on the resource status presented in Fig. 25. NRR Zone 1 (NRRZ1-361 grids) represents the richest natural resources regions (which are also ecologically fragile), followed by NRRZ2 (464), NRRZ3 (879) grids, and NRRZ4 (888 grids), indicating the least resource available grids (least ecological significant/high resource exploitation). The Western Ghats districts - Uttara Kan-

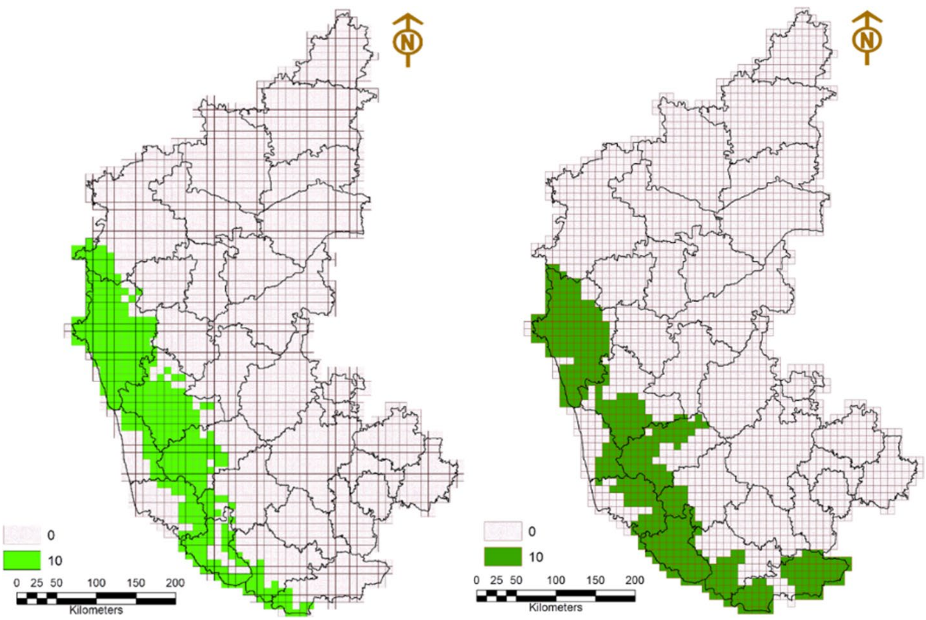

Fig. 24 Ecosensitive regions with weights (across grids) in Western Ghats districts as per WGEEP and HLWG

nada, Shimoga, Kodagu, Chikmagalur, Dakshina Kannada, Mysore, and Chamarajanagar, show the large tract under NRRZ1, necessitating protection to ensure the sustenance of natural resources. Yadgir, Kalaburgi, and Bijapur showed a higher area under NRRZ3 and NRRZ4, respectively. The taluk-wise NRRZ regions are also shown in Fig. 26, which

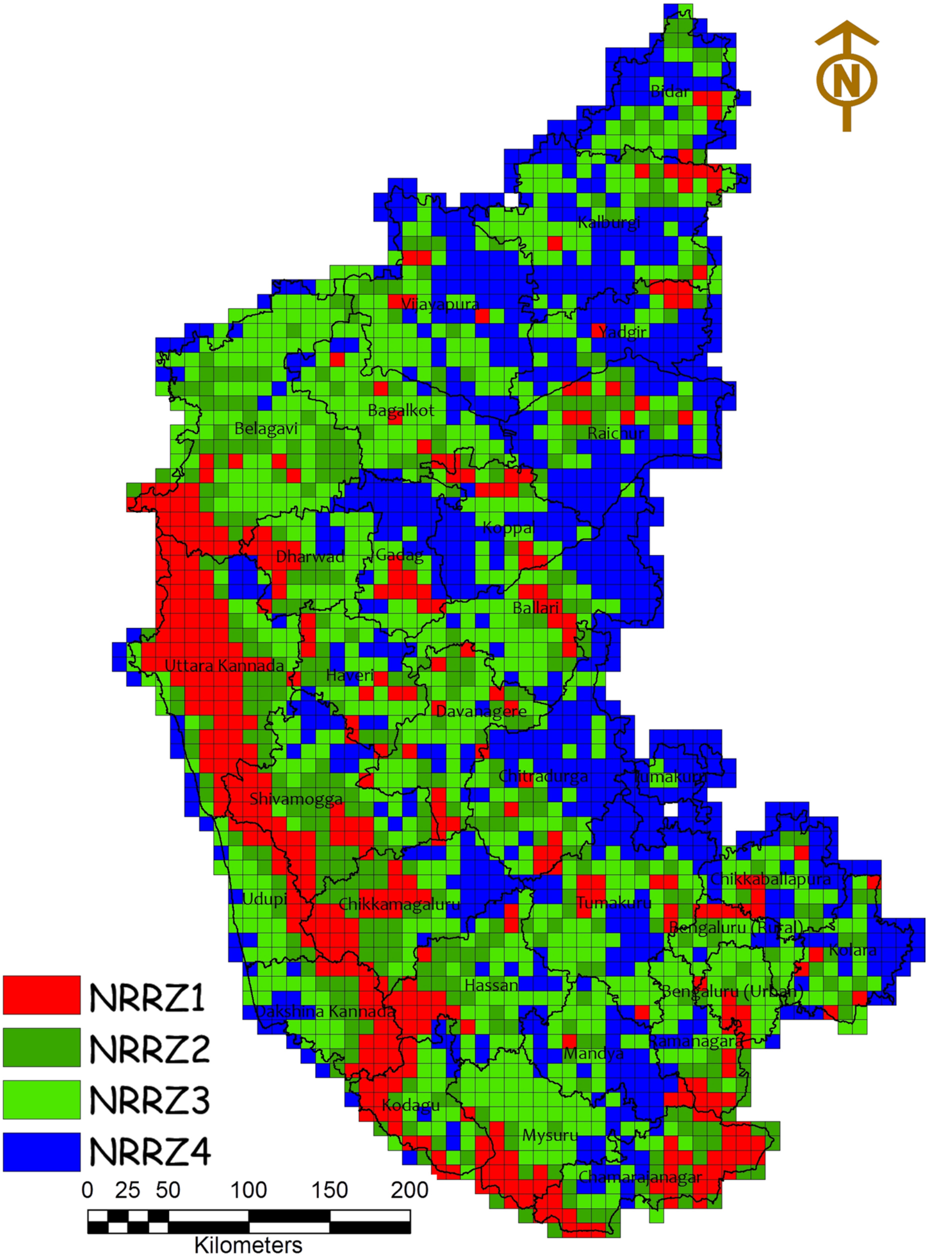

Fig. 25 NRRZs of Karnataka state

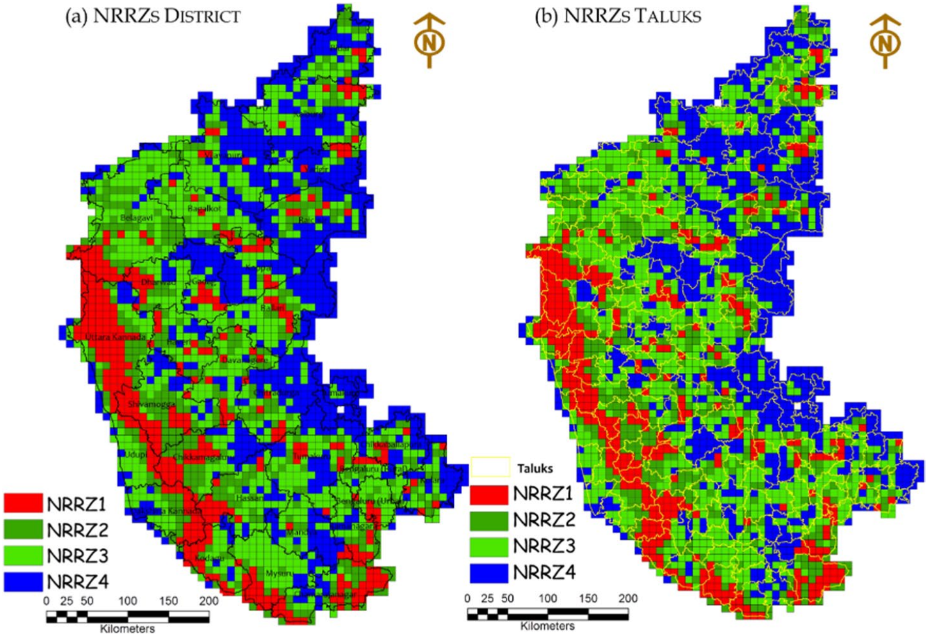

Fig. 26 NRRZs of Karnataka district wise, and taluk wise

depicts 42 taluks as NRRZ-1, 24 taluks as NRRZ-2, 51 taluks as NRRZ-3; and the rest of 61 taluks as NRRZ-4.

3.10 Discussion: management of NRRZs

The management of NRRZs entails protecting natural resources to improve the quality of life of both the present and future generations (stewardship or sustainability) through effective, prudent planning. The management includes land use planning, water and other resources management, and biodiversity conservation to protect natural landscapes and people's livelihoods. Maintaining NNRZ from further degradation will support people's livelihood through improved health and productivity. NRRZ management recommendations also focus on allowable activities by focusing on the future sustainability of agriculture, mining, tourism, fisheries, and forestry activities. The suggestions help to address unregulated resource usage, unplanned urbanization, and other developmental activities (Table 3). NRRZ4, and NRRZ3 areas act as a **'Shock Absorber'**, so regulated activities in these regions can enrich NRRZ1 and 2. They also act as a **transition zone** from areas of high protection to areas involving lesser protection. Policy measures required to sustain natural resources in Karnataka are:

- The NRRZ1 represents a zone of highest conservation, with stringent norms to prevent further degradation. NRRZ2 has the potential to become NRRZ1, provided with strict regulations and the improvement of forests and their environs through implementation of conservation protocol. A small change in NRRZ2 will have more adverse effects in NRRZ1.

- No new major/expansion of roads or railway lines are allowed in NRRZ1, as 90% of the region falls under ecological fragility and is susceptible to vulnerabilities (landslides, flooding, etc.). The necessity of expansion should be subjected to EIA (environmental impact assessment) and strict monitoring based on the social audit.
- Forest Rights Act to be implemented in its true spirit by ensuring genuine stakeholders are not deprived of their rights.
- Monoculture plantations of exotic species need to be regulated in NRRZ, and existing exotics should be replaced by planting endemic species.
- Monoculture exotic species need to be restricted in coffee plantations of NRRZ1.
- Promote decentralized energy through incentives for harvesting decentralized renewable energy sources (solar, wind, bioresources).
- The local bio resource-based industry be promoted with strict regulations and subject to social audits.
- Adapt development projects that will have the most negligible environmental impact by involving local community members in decision-making and environmental monitoring.
- The tourism Master Plan should be based on MoEFCC regulations (after considering social and environmental costs). Restrictions will be imposed on the construction of large resorts (hotels/restaurants) and new tourism establishments in NRRZ1.
- Controlled activities are permitted based on socio-economic importance, and activities such as alteration of ecologically sensitive wetlands and natural forests or the introduction of alien invasive species are not permitted.

Activities (sector-wise) allowed and regulated across various NRRZ are.

(i) Energy – promoting solar (rooftop) energy in all zones, wind, and bioenergy (in all zones except NRRZ1),
(ii) Forests – strict regulation on land-use changes (forest to other land uses), restrictions on monoculture plantations, permission to collect NTFP, and forest management by involving all stakeholders through VFCs in all zones. Extraction of medicinal plants on a sustainable basis in NRRZ3 and NRRZ4,
(iii) Agriculture – agroforestry, organic farming, and animal husbandry in all zones with a complete ban on genetically modified crops,
(iv) Horticulture – ban on the use of hazardous endosulfan in all zones, prohibition on the use of nitrogen and phosphorous (N & P) fertilizers, pesticides only in NRRZ 4, watermelon, muskmelon, ginger cultivation only in NRRZ3 and NRRZ4,
(v) Industries (Large scale): promotion of agro-processing industries in all zones, ban on red category (polluting) industries in all zones, promotion of green (non-polluting) industries, information technology (IT) and garment industries in NRRZ 3 and NRRZ 4, new establishment of industries only in NRRZ4 (allowed only after critical review by local stakeholders and experts),
(vi) Industries (Small scale): promotion of domestic (home-based industries such as papad, mango processing, milk products, and processing, dry fruits and spices, Fruit processing (Ex: Kokum Juice *(Garcinia indica)*), Fish products processing, Beekeeping, and bee nurseries, Vegetable dyes; fruits and vegetable preservation, Medicinal plants cultivation and processing) in all zones and promotion of industries such as Areca nut

processing & Coir industries, Pongamia plantations for biofuel (in private lands), Biopesticides manufacturing, Poultry farms, and powdered eggs, Aromatic plants and essential oil distillation; orchids and cut flowers harvesting industries and Garment industries in NNRZ 2, NRRZ 3 and NRRZ 4,

(vii) Tourism: promotion of activities such as Organic village and homestay, VFC-managed tourism, Arts and handicrafts museum, and trade center in all zones, promotion of eco-tourism in NRRZ2, NRRZ 3 and NRRZ4,

(viii) Mining and Mineral extraction – permission to Sand extraction (on a sustainable basis by a ban on exporting) in NRRZ 3 and NRRZ 4, extraction of quartz, limestone, etc. in NRRZ4, ban on large-scale extraction of iron ore, manganese, and bauxite in NRRZ 1 and 2,

(ix) Waste disposal – ban on hazardous waste processing units in NRRZ1, NRRZ 2, and NRRZ 3, permission to Solid waste disposal, Liquid waste discharge, and Recycling and waste processing units only in NRRZ 4,

(x) Transportation – Linear projects (roads and expressways) online NRRZ 4, Railway and freight corridor, Up-gradation of existing infrastructure in NRRZ 3 and NRRZ 4.

4 Conclusion

The conservation and sustainable management of ecosystems are vital components in the pursuit of ecologically sound, economically viable, and socially acceptable development goals. Sustainable land use management policies help in addressing abrupt transitions efficiently and assist in optimal resource usage, mitigating the environment impacts at the local and global scales. However, the development of prudent management policies necessitates a detailed understanding of functioning ecosystems, diversity of natural resources, economic values, and ecosystem services. The current research has prioritized the natural resources-rich zones (NRRZ) at disaggregated levels (Panchayat levels – administrative unit as per the 73rd and 74th Constitutional Amendment Acts, 1992 for ensuring local self-governance through empowering local bodies, and Biodiversity Act, 2002, GoI) in Karnataka state based on the integrated approach of aggregating bio-geo-climatic, land, ecological, energy, and social variables. The current approach is significantly superior to traditional conservation planning approaches, which operate at coarser resolutions with a single theme that often remains disconnected from implementation realities. The integration of scientific rigour with administrative pragmatism offers a valuable model for evidence-based environmental management in complex socio-ecological systems. The NRRZ procedure's strength is the replicability for real-world conservation governance and prudent management of natural resources.

The forest cover accounts for 15% (in 2019) compared to 21% earlier (1985), highlighting the anthropogenic pressure leading to forest degradation with deforestation. The districts of the Western Ghats region have higher forest cover than other districts. Post-1990s, the state has witnessed large-scale land use transitions due to globalization leading to industrialization, rapid urbanization, an increase in horticulture crops, conversion from agriculture to market-based crops (higher economic), etc. The grid-wise assessment shows 14% (361 grids) of the state's area under NRRZ-1, 18% (464 grids) under NRRZ-2, 34% (879 grids) under NRRZ-3, and 888 grids accounting for 34% area as NRRZ-4. 32% of the state's area highlights the need to conserve the resource-rich status and sustain natural resources. Considering the ecological fragility, there shall be no activity that would alter the physical and chemical integrity of the Western Ghats region. It is recommended to preserve, protect, and improve the quality of the environment through stakeholder engagement to ensure protecting livelihood of people, health, and utilisation of natural resources prudently and rationally within the ecosystem's carrying capacity. Implementation of recommendations would aid in curtailing abrupt land cover transitions while supporting appropriate decision-making toward progressive and ecologically sound development.

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