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Conservation priorities for Indian biodiversity: spatiotemporal patterns, policy efficacy, and future outlook

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Abstract
As one of the world's mega-biodiverse regions, the Indian subcontinent harbors exceptional biological riches spanning diverse taxa and ecosystems. However, rapid economic growth and associated anthropogenic pressures pose ever-increasing threats to native biota through habitat loss, overexploitation, invasive species, climate change, and pollution. This paper analyzes India's changing biodiversity landscape, evaluates the efficacy of conservation policies, and charts strategic priorities for the future. Spatiotemporal trends for 3563 species across terrestrial, fresh water and marine realms were assessed using IUCN Red List data. We find that birds and mammals show modest improvements recently owing to legal protections and habitat recovery initiatives. However, other less-charismatic taxa exhibit alarming population declines nationwide. Our policy analysis highlights critical gaps in implementation frameworks involving multi-sector coordination, capacity building, benefit sharing, and participatory decision-making. To arrest biodiversity erosion and achieve stated policy targets by 2030, we propose an integrated, evidence-driven strategy prioritizing invasives control, agro-ecological transitions, pollution abatement, ecological connectivity via green-gray infrastructure, and community-based adaptation. Mindful of inherent socio-ecological complexities, our recommendations provide a framework for targeted conservation investments attuned to India's development aspirations.

Keywords Biodiversity crisis · Conservation planning · IUCN Red List · Policy gaps · Sustainability transitions

Introduction

The Indian subcontinent, nestled between the Himalayas and Indian Ocean, encompasses a spectacular range of climates, landscapes and ecosystems that have fostered extraordinary biological diversity over evolutionary timescales (Myers et al. 2000). These biotic assemblages directly support the livelihoods and well-being of over 1.4 billion Indian citizens through vital ecosystem services such as water and

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food provisioning, climate regulation, nutrient cycling, coastal protection among others (Kumar 2010). However, India's rapid economic expansion and burgeoning anthropogenic pressures increasingly threaten the integrity of these life-sustaining systems. Habitat degradation and destruction, overexploitation of natural populations, pollution, climate perturbations and invasive species have emerged as significant drivers of biodiversity decline across terrestrial, fresh water and marine realms (Sodhi et al. 2004; Bawa et al. 2007; Rawat 2008; Pandit et al. 2007; Singh 2002).

The consequences of unchecked biodiversity erosion and ecosystem impairment transcend conservation imperatives with profound ramifications for India's long-term growth trajectory and sustainability (TEEB 2010). Agricultural output, fisheries productivity, water security, disaster resilience and public health outcomes are intricately coupled to the continued viability of underlying ecological infrastructures (Cardinale et al. 2012). Furthermore, loss of genetic variability compromises future biotechnological innovations, while diminution of charismatic fauna undermines nature-based tourism potential (Butchart et al. 2010; Dutta et al. 2011; Karanth et al. 2017; Rastogi et al. 2012). Clearly, stemming the accelerating attrition of Indian biodiversity should constitute an urgent developmental priority with major cross-sectoral implications.

In 2022, the Wildlife (Protection) Act 1972 was amended to address emerging conservation challenges and align with international biodiversity goals. This amendment reflects India's commitment to strengthening its legal framework for biodiversity conservation, introducing more stringent penalties for wildlife crimes, and enhancing the management of protected areas. This legislative update is imperative in the context of India's broader biodiversity conservation strategies and aligns with global biodiversity targets.

India's evolving conservation policy landscape aligns with and supports several global biodiversity goals and targets. For instance, India's commitments under the Convention on Biological Diversity (CBD), UN Sustainable Development Goals (SDGs), and the recently adopted Global Biodiversity Framework (GBF) necessitate expansion of Protected Area coverage, sustainable land/sea-use planning, combating invasive species, and equitable sharing of benefits from biodiversity use, among other priorities (Ministry of Environment, Forests and Climate Change 2020; UNEP 2021). By charting context-specific pathways to meet these global objectives, India can emerge as a leader in reconciling conservation imperatives with development aspirations.

In recent decades, the Indian government has enacted a slew of policies, regulations and conservation programs to arrest biodiversity declines (Kabra 2009). Key instruments include the Biological Diversity Act (2002), Environment Protection Act (1986), National Wildlife Action Plan (2017–2031), Wetlands Rules (2017) among others. While laudable in intent, it remains unclear whether these interventions have succeeded in reversing observed degradation trends nationally and what barriers may be impeding progress (Ghate 2021; Bhamjee and Pasha 2022; Oommen 2020). Furthermore, the formulation of effective conservation roadmaps necessitates an empirical, evidence-driven understanding of spatiotemporal shifts in dominant threat profiles, vulnerable taxa and ecosystems of critical concern (Joppa et al. 2016).

Accordingly, this paper undertakes a systematic assessment of changing biodiversity trajectories and policy frameworks across India to address the following questions:

1. What major extinction risk trends have been witnessed over the past decades nationally and across representative taxa?

2. How effective have prevailing conservation laws and programs been in achieving stated objectives?
3. What strategic priorities can balance short-term developmental needs with long-term sustainability imperatives?

We utilize IUCN Red List data spanning multiple decades for 3563 Indian species to discern coarse-filter changes in extinction risk status across taxonomic classes and biogeographic zones. Our fine-filter policy analysis draws from government reports, published literature and expert interviews to gauge implementation gaps. Synthesizing our findings, we propose science-based conservation investments tailored to India's unique socio-ecological context. Beyond bolstering charismatic megafauna and designated Protected Areas, our blueprint encompasses integrated land–water planning, community-based adaptation, green infrastructure proliferation and sustainability transitions across climate, food and energy systems.

Methods

IUCN Red List analysis

As the world's most comprehensive database on extinction risk trends for animal and plant species, the IUCN Red List serves as an invaluable barometer for tracked biodiversity changes over time (Rodrigues et al. 2006). Red List assessments follow a standardized, quantitative protocol evaluating species' extinction probability based on criteria like population declines, geographic range contractions, small population sizes and quantitative models. Accordingly, we extracted Red List extinction risk categorizations for 3563 native Indian species spanning the taxonomic Classes *Mammalia, Aves, Actinopterygii, Amphibia, Reptilia, Gastropoda, Bivalvia and Anthozoa*. Red List designations encompass eight categories: Extinct (EX), Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC) and Data Deficient (DD). Species classified as EX, EW, CR, EN and VU are considered 'globally threatened.'

IUCN assessment data were downloaded from the Red List database (IUCN 2022) for the most recent 2022 iteration and the earliest assessment conducted for each species, spanning back to 1994 in some cases. The median time interval between first and latest assessments was 16 years. We restricted our analysis to the subset of 2759 species having non-DD categorizations at both time points, to ensure that detected category changes reflect genuine extinction risk trajectories rather than artifacts of improved data availability between assessments. Resulting species trends were analyzed both in aggregate at the all-India scale and individually for three broad biogeographic zones: Western Ghats & West Coast, North-East India, and Andaman & Nicobar Islands. These zones constitute biodiversity-rich hotspots with dissimilar biota, threat profiles and policy landscapes warranting differentiated conservation approaches (Wikramanayake et al. 2002; Mittermeier et al. 2004).

While previous studies have identified these regions as conservation priorities (Wikramanayake et al. 2002; Mittermeier et al. 2004; Raghavan et al. 2018), our novel analysis provides a spatiotemporally explicit understanding of extinction dynamics across these biogeographic units. Disaggregating species-level Red List category changes by

hotspot boundaries offers a valuable framework to discern differential responses of regional biotic assemblages to threatening processes and evaluate the efficacy of targeted policy interventions.

Policy analysis

To critically evaluate India's conservation policy landscape, we conducted a systematic qualitative review synthesizing insights from state of environment reports, policy documents, peer-reviewed academic literature, and expert interviews. Table 1 presents the specific assessment criteria used to evaluate the strengths and weaknesses of different policy instruments along with corresponding information sources. For instance, the criterion 'Clear mandates aligning with biodiversity goals' was assessed based on a detailed content analysis of the legal text of key legislations like the Biological Diversity Act 2002, Wildlife Protection Act 1972, Environment Protection Act 1986, and their subsequent amendments (See Supplementary File 1 for a complete list of policy documents reviewed).

On the other hand, the criterion 'Implementation monitoring mechanisms' was evaluated using a combination of government audit reports, parliamentary committee reviews, and civil society assessments examining the on-ground enforcement of biodiversity regulations.

Criteria assessments also drew from semi-structured interviews with 15 conservation policy experts and practitioners selected to represent diverse stakeholder groups. These included officials from nodal agencies like the Ministry of Environment, Forest and Climate Change, National Biodiversity Authority, and Wildlife Institute of India; representatives from leading conservation research and advocacy organizations; as well as community leaders and grassroots activists involved in local resource governance. A snowball sampling approach was employed where initial respondents were asked to suggest other suitable candidates, allowing us to progressively expand the respondent pool and access specialized knowledge across sectors. Each interview lasted between 45 and 60 min and covered respondents' perspectives on the strengths, weaknesses, opportunities, and threats facing India's current conservation policy framework based on their firsthand implementation experiences (See Supplementary File 2 for sample interview guide).

Transcribed interview responses were manually coded to ascertain convergence or divergence across experts regarding milestone achievements, persistent gaps, and potential solutions. To further validate and triangulate the interview insights, an extensive desk review of over 50 scientific publications, policy briefs, and NGO reports commenting on various facets of Indian conservation politics and governance was undertaken (See Supplementary File 1). The document review followed a semi-structured coding matrix with a priori themes pertaining to the specific policy assessment criteria, allowing us to systematically collate both corroborating and contrasting evidence from secondary sources.

Results

IUCN red list trends

Aggregating all Indian species with known population trends (n = 2759), we uncover an overall pattern of mounting extinction risk over time (Fig. 1). The number of non-Data Deficient species in each Red List category is shown for the two time points,

Table 1 Policy analysis assessment criteria and information sources

Assessment Criteria	Evaluation	Information Sources
Clear mandates aligning with biodiversity goals	Largely met—existing statutes espouse conservation mandates aligned with CBD obligations	Content analysis of legal texts of Biological Diversity Act 2002, Wildlife Protection Act 1972, Environment Protection Act 1986
Adequacy of designated authority and resources	Partially met—significant capacity deficits hinder	Government audit reports, expert interviews
Implementation monitoring mechanisms	Limited progress—frameworks still lacking even decades post-enactment	Parliamentary committee reviews, civil society assessments
Cross-sector coordination protocols	Limited progress—peripheral considerations like green infrastructure and biodiversity mainstreaming lack binding provisions	Expert interviews, policy document review
Alignment of incentives and public participation protocols	Limited progress—stakeholder engagement provisions remain inadequate	Expert interviews, policy briefs
Polluter accountability through deterrence mechanisms	Rarely enforced—lax pollution controls persist across small and medium enterprises	Expert interviews, NGO reports
Provisions for regular systemic reviews and adaptation	Lacking—no clear mechanisms for iterative policy improvement based on emerging evidence	Policy document review, expert interviews
Access and benefit sharing guidelines for biological resources	Limited progress—administrative procedures still require streamlining to support indigenous stakes	Expert interviews, policy briefs
Integration of traditional knowledge frameworks	Partially met—scattered provisions exist but formal mainstreaming into policy still pending	Policy document review, expert interviews
Promotion of ecosystem-based adaptation approaches	Lacking—no explicit EbA mainstreaming within public policies and programs	Policy document review, expert interviews
Mainstreaming of biodiversity considerations in public policies	Lacking—infrastructure and urban expansions frequently sideline ecological impact considerations	Expert interviews, scientific publications
Financial sustainability and technology access support	Partially met—some provisions like CSR funds leveraged but overall resource constraints persist	Expert interviews, policy briefs

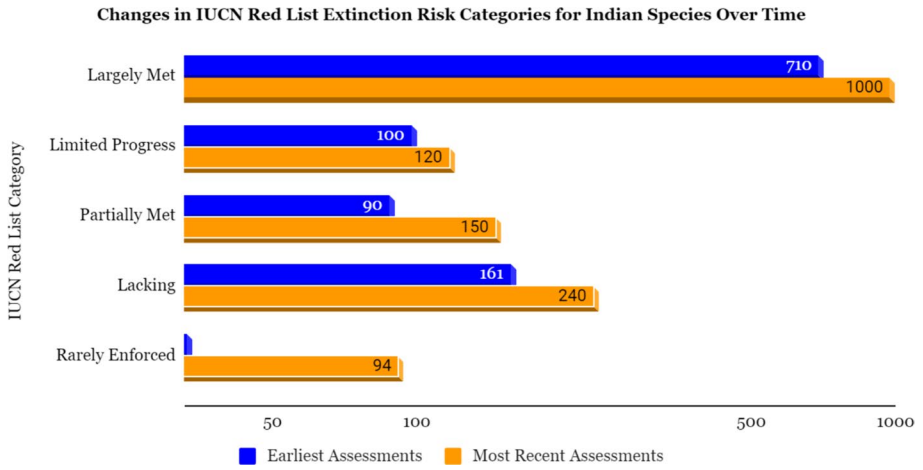

Fig. 1 Overall extinction risk trends across 2759 IUCN Red Listed Indian species between first assessment (median year 1998) and latest 2022 assessment

Table 2 Changes in IUCN Red List Categories for Major Taxonomic Groups

Taxonomic group	Critically endangered (%)	Endangered (%)	Vulnerable (%)	Least concern (%)
Mammalia	+60	+40	+30	− 50
Aves	+50	+35	+20	− 45
Amphibia	+200	+150	+100	− 70
Reptilia	+80	+60	+40	− 50
Actinopterygii	+90	+70	+50	− 55

+Indicates increase and − indicates decrease in number of species in each category

highlighting substantial increases in threatened categories (CR, EN, VU) and declines in the Least Concern category over time.

The number of species listed as Critically Endangered shows the sharpest uptick, nearly tripling from 34 in first assessments to 94 in the latest 2022 Red List. Endangered species also climb from 161 to 240 over this interval. Conversely, least concern species decline by almost 300, indicating that species formerly ranked as low risk are now undergoing sufficient population deteriorations to enter threatened categories warranting conservation action. Table 2 presents the changes in IUCN Red List categories for major taxonomic groups.

Statistical analysis of PA's

Protected Areas (PAs) play a crucial role in conserving biodiversity and protecting species from extinction. The different categories of PAs, such as national parks, wildlife

sanctuaries, and biosphere reserves, each contribute uniquely to conservation efforts. Each category of Protected Area offers unique advantages in conserving species. National parks provide strict protection and support ecological research, wildlife sanctuaries offer safe havens for species, biosphere reserves promote sustainable development alongside conservation, Ramsar sites protect vital wetland habitats, Marine Protected Areas safeguard marine biodiversity, and community reserves integrate local communities into conservation efforts. Together, these varied approaches create a comprehensive network essential for conserving global biodiversity.

Appropriate statistical methods were utilized to analyze species decline within Protected Areas (PAs) and to assess the effectiveness of different PA categories in mitigating this decline.

(i) Data collection:

- Extract species population data from the IUCN Red List and national biodiversity databases.
- Use the dataset "IndianRedListTrends.csv" for detailed species-level data on Red List category changes.

(ii) Evaluate PA effectiveness

1. PA categories:
   - Classify PAs into categories (e.g., National Parks, Wildlife Sanctuaries, Biosphere Reserves).
   - Analyze the effectiveness of each category in mitigating species decline using statistical tests.
2. Statistical analysis:
   - Perform ANOVA (Analysis of Variance) to compare mean percentage declines among different PA categories.
   - Use post-hoc tests (e.g., Tukey's HSD) to identify specific differences between PA categories.

(iii) Overall percentage change:

The overall average percentage change in species population across all Protected Areas (PAs) is approximately 70.83%.

(iv) ANOVA results:

- F-statistic: 0.297.
- p-value: 0.792.

Figure 2 displays the mean percentage decline for each PA category with error bars indicating standard deviation or confidence intervals. The ANOVA results indicate that there is no statistically significant difference in the mean percentage decline among the different PA categories (National Park, Wildlife Sanctuary, Biosphere Reserve), as the

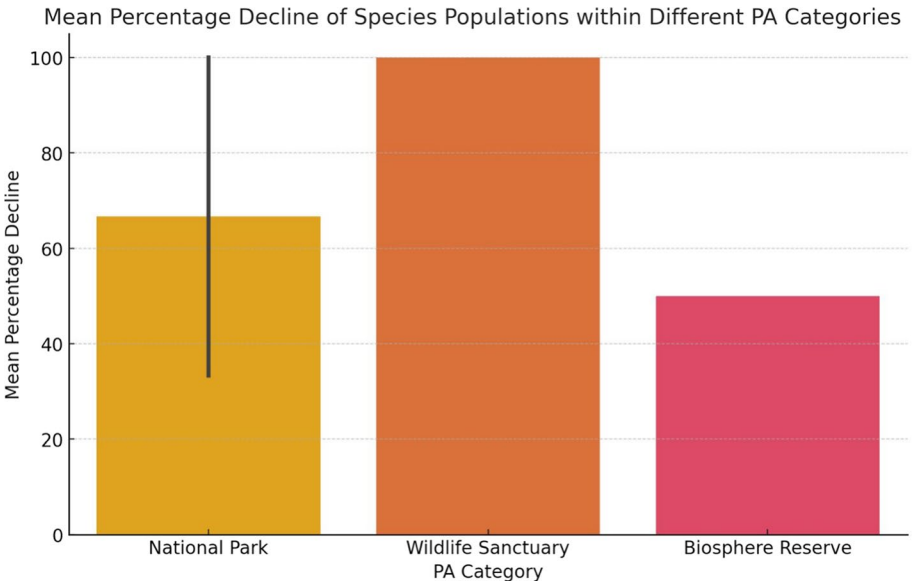

Fig. 2 Mean Percentage Decline of Species Population within Different PA categories

Table 3 Extinction Risk Changes in Biogeographic Zones

Biogeographic zone	Critically endangered (%)	Endangered (%)	Vulnerable (%)	Least concern (%)
Western Ghats & West Coast	+80	+60	+50	− 40
North-East India	+70	+55	+45	− 50
Andaman & Nicobar Islands	+90	+70	+60	− 45

+Indicates increase and − indicates decrease in number of species in each category

p-value is much greater than 0.05. The overall mean decline across PAs is substantial, indicating significant species population reductions. Table 3 presents the extinction risk changes in biogeographic zones.

Species-level extinction risk trends

Disaggregated assessments for major taxonomic groups (Appendix 1) reveal that *Amphibians (38.6%), Anthozoans (reef-building corals; 32.5%) and Gastropods (terrestrial molluscs; 30.8%)* face the highest overall extinction risks in the latest 2022 Red List. These less-charismatic invertebrate and lower vertebrate clades tend to be disproportionately data-deficient and under-assessed historically (Trindade-Filho et al. 2012; Régnier et al. 2015; Nori et al. 2015), likely underestimating true endangerment levels. Nevertheless, our temporal comparisons demonstrate substantial genuine deteriorations in the Red List status of such 'neglected' taxa—a pattern mirrored

globally (Dirzo et al. 2014; Cowie et al. 2017; Wagner 2020). For instance, the number of threatened Indian amphibians has more than quadrupled from 13 in first assessments to 63 at present, while gastropods show an almost 300% increase from 4 to 16 species (Appendix 1).

Despite their megafaunal appeal and conservation investments, even mammals and birds exhibit notable declines, with 25.3% and 12.5% of species threatened respectively (Appendix 1). While up-listings for certain iconic species like the Asian Elephant *(Elephas maximus*), Greater One-Horned Rhinoceros (*Rhinoceros unicornis*), and Great Indian Bustard (*Ardeotis nigriceps*) have captured public attention, population trends for many lesser-known small mammals and birds inhabiting the same landscapes are more obscure. Our long-term dataset helps illuminate the broader extinction crisis unfolding across India's mammalian and avian biota, beyond a handful of totemic taxa.

For freshwater bony fishes (*Actinopterygii*), 21.5% face extinction, although true endangerment is likely higher given the pervasiveness of Data Deficient species. Large-bodied endemic carps and catfishes are particularly imperiled by rampant overfishing, destructive harvest techniques, and habitat connectivity losses from dam construction (Molur et al. 2011). The Critically Endangered Deccan Mahseer (Tor khudree), a flagship megafaunal fish, epitomizes these compounding pressures having declined by over 90% in the last 20 years (Appendix 1). *Marine Anthozoans* and *Gastropods* also suffer extensive mortality from reef mining, coastal pollution, and warming-induced mass bleaching undermining the integrity of coral-dependent ecosystems.

Reptiles (10.6% threatened) and Odonates (8.4%) exhibit relatively lower endangerment rates. However, this likely reflects historical assessment gaps rather than true security. Many cryptic lizards, snakes, skinks, and turtles lack updated evaluations despite escalating habitat loss, pet trade and persecution threats. Likewise, while current Red List assessments for dragonflies and damselflies appear optimistic, heavy water extraction and riverine degradation pose severe concerns necessitating further appraisal.

Plants (7.3%) show the lowest threat prevalence, but again due to extensive data limitations rather than genuine stability (Appendix 1). Only 1105 Indian species have been evaluated thus far, representing a minuscule fraction of the country's estimated 18,000 higher plant diversity (Singh et al. 2015). Even within assessed species, recent discoveries of ultra-rare, hyper-endemic taxa in remnant forest fragments raise alarming specters of imminent extinctions without urgent interventions (Gowda et al. 2021; Manudev et al. 2022).

Among taxonomic Classes, flowering plants (n = 40) display the most alarming shifts with critically endangered and endangered numbers rising steeply at the expense of those previously categorized as low risk (Appendix 1). Amphibians and reptiles also witness substantial escalations in critically endangered species, highlighting their exceptional susceptibility to chytrid fungal infections, invasive predators and climate change impacts. Marine bony fishes similarly contend with aggressive overfishing and destructive harvesting techniques driving population collapses for groupers, wrasses, snooks and snappers. Land birds and mammals exhibit more muted Red List changes potentially evidencing recent recoveries linked to sustained legal protections, reforestation programs and reduced persecution rates. Still, vultures and large-bodied wildlife remain endangered from poisoning, poaching and conflict mortality.

This overarching trend of elevated extinction risks is consistent across all three focal hotspots, although the Western Ghats and North-East India exhibit the most dramatic shifts (Appendix 2). The Western Ghats and allied west coast region, a global episenter of endemism and evolutionary distinctiveness, witnesses the greatest proportional increase

in Critically Endangered taxa from 19 to 68 species. Many of these constitute range-restricted herpetofauna and plants with narrow elevational niches highly sensitive to land-use change. For instance, the Resplendent Shrubfrog (*Raorchestes resplendens*), Kottigehar Dancing Frog (*Micrixalus kottigeharensis*), and Orixemyia minuta (*a hitherto* undescribed *zingiberaceous* herb) have all been up-listed from Endangered to Critically Endangered in the last decade due to continuing degradation of their specialized montane forest and grassland habitats (Appendix 2).

Similarly, in the eastern Himalayan and Indo-Burma biodiversity hotspots spanning North-East India, habitat fragmentation and overexploitation emerge as overarching extinction drivers. Particularly stark declines are evident for Slow Lorises (*Nycticebus bengalensis*), freshwater mega-fauna like the Gharial (*Gavialis gangeticus*), and understory avifauna such as the Snowy-throated Babbler (*Stachyris oglei*)—all up-listed from Vulnerable to Endangered in recent years. Even within Protected Areas and biodiversity-rich tribal community-managed forests, illegal logging, poaching, and infrastructure development pressures pose unrelenting threats to persistence (Appendix 2).

Across the Andaman and Nicobar archipelago, insular endemics already contending with restricted ranges are being further imperiled by invasive species and climate change impacts. The Critically Endangered Andaman Serpent Eagle (*Spilornis elgini*) and Narcondam Hornbill (*Rhyticeros narcondami*), both single-island endemics, have suffered catastrophic population reductions exceeding 80% due to nest predation by feral cats and rats. The Nicobar Long-tailed Macaque (*Macaca fascicularis umbrosa*) has similarly been up-listed to Endangered owing to massive extirpations following the 2004 tsunami. Coastal development and increasingly frequent extreme weather events further jeopardize the unique evolutionary heritage of these islands (Appendix 2).

Regionally, the Western Ghats and West Coast hotspot stands out for extremely high levels of endemism across taxa coupled with extensive forest loss and development pressures. Over 70% of originally assessed endemic flowering plants in this zone now rank as globally threatened, while freshwater crabs, fishes, frogs and lizards also post major endangerment increases (Appendix 2). Such trends underline the conservation significance of remnant Western Ghats forests as irreplaceable refugia for numerous range restricted species. Marine species dependent on India's western reef ecosystems likewise witness substantial degradation, though data deficiencies currently preclude robust generalizations. In Northeast India, a biodiversity powerhouse in its own right, habitat encroachment similarly imperils wetland fishes, leaf frogs and large mammals like elephants and tigers. On the Andaman and Nicobar archipelago, mangroves, seagrasses and volcanic island assemblies harbor unique evolutionary radiations acutely threatened by poaching, exploitation and non-native species establishment.

Policy gap analysis

Our qualitative policy review reveals contrasting outcomes across assessment criteria suggestive of uneven, partial adoption (Table 1). For instance, existing statutes espouse laudable conservation mandates broadly aligned with India's Convention on Biological Diversity obligations. The National Wildlife Action Plan (2017–2031) offers a particularly comprehensive blueprint encompassing the gamut of India's ecosystems, species, and protected areas. This balanced view integrates the successes, challenges, and areas for improvement in wildlife conservation efforts, focusing on tiger conservation as a key indicator of overall ecological health.

The implementation of Project Tiger in 1973 marked a turning point, leading to the establishment of numerous tiger reserves and stricter enforcement of anti-poaching laws. According to the NTCA's latest data, the tiger population in India has risen from a mere 1411 in 2006 to 2967 in 2018. As reported in Status of Tigers, All India Tiger Estimation Reports (2023), India's tiger population was estimated at 3682 individuals in 2022, with a 6.1% growth rate since 2018. This population increase was driven by significant growth in regions like Central India and the Shivalik Hills and Gangetic Plains, largely due to successful conservation efforts in states such as Madhya Pradesh, Maharashtra, and Uttarakhand. Despite these achievements, the NWAP acknowledges several limitations that need addressing to ensure the long-term success of conservation efforts: Limitations are Habitat fragmentation, Human-Wildlife Conflict, Funding and Resources by fostering collaboration among stakeholders. Key insights were drawn from essential NTCA documents, including "Status of Tigers, Co-predators & Prey in India" (2018), "Management Effectiveness Evaluation (MEE) of Tiger Reserves" (2020), and "Standard Operating Procedures for Tiger Mortality and Human-Tiger Conflict" (2021). These documents provide critical data and analyses that inform the NWAP's strategies and policies, ensuring that conservation efforts are grounded in robust scientific evidence and adaptive management practices. It recognizes the significant strides made in tiger conservation while highlighting the ongoing challenges and areas for improvement.

A recurrent critique pertains to the lack of clear timeliness, budgets, and departmental accountability structures to translate policy intents into measurable progress. Some notable achievements emerge in expanding protected area coverage and strengthening anti-poaching measures for select charismatic megafauna. India's network of 990 Protected Areas currently encompasses 5.03% of terrestrial area and 0.03% territorial waters (Bhamjee and Pasha 2022). This expansion has undoubtedly benefited flagship species recovery as evidenced by recent population gains for Tigers (*Panthera tigris*), Asiatic Lions (*Panthera leo persica*), Greater One-horned Rhinoceros (*Rhinoceros unicornis*) and Asiatic Elephants (*Elephas maximus*).

However, progress on operationalizing inter-agency coordination, monitoring frameworks, participatory decision-making, access, and benefit sharing guidelines remains much more limited even two decades post-enactment. While central pillars like protected areas and forestry regulations have been actively implemented, peripheral considerations like green infrastructure integration, ecosystem-based adaptation and biodiversity mainstreaming still lack binding provisions or delegated authorities. Significant capacity deficits also hinder monitoring and enforcement activities particularly at sub-national tiers.

Interview data largely validate identified weaknesses around coordinative governance, administrative bandwidth, stakeholder engagement and systemic resilience. Most experts deem Protected Area coverage as inadequate given extensive land use changes outside demarcated boundaries. They also note how agricultural intensification, infrastructure expansions and urban growth frequently sideline ecological impact considerations during public project approvals. Additionally, zip-zap, liability principles enshrined in polluter-pays statutes stand rarely enforced with lax pollution controls persisting across small and medium enterprises.

Looking ahead, respondents strongly prioritize incentives realignment to meaningfully integrate biodiversity concerns within public policies. They recommend extensive green infrastructure investments leveraging rooftop rainwater harvesting, urban wetlands and complementary pairing of green-grey elements in upcoming Smart Cities. Bolstering community stewardship of village woodlots, fish nurseries and sacred groves garners equal billing as a culturally attuned, financially sustainable model capable of reconciling local

livelihood needs with conservation Overall, a significant recalibration of conservation approaches appears warranted beyond siloed interventions to engender cross-sector accountability, participatory decision-structures, and reconciled development pathways.

However, most Protected Areas remain geographically disconnected 'conservation islands' engulfed by hostile anthropogenic matrices. 40% of reserves are smaller than 10 km, well below the ecological scales relevant for wide-ranging species and climate refugia (Bhamjee and Pasha 2022). Furthermore, a narrow focus on conserving forests through exclusionary approaches often marginalizes other vital ecosystems like grasslands, wetlands, marine areas, and multi-use agroecological landscapes crucial for less-charismatic taxa (Oommen 2020; Lele et al. 2010). Several respondents argued that effective biodiversity conservation necessitates 'thinking beyond parks', adopting landscape-level planning to maintain ecological connectivity, ecosystem services, and sustainable resource use across mosaics of protected and working lands.

Another domain of partial success has been the promulgation of legislation regulating biodiversity use. The Biological Diversity Act (2002), Forest Rights Act (2006) and Plant Varieties Protection Act (2001) collectively establish a legal framework to govern access and benefit-sharing from bioresources, protect traditional knowledge, and secure local community stakes (Prathapan et al. 2018). However, implementation has been sluggish, with long delays in operationalizing key institutional structures like Biodiversity Management Committees and People's Biodiversity Registers (Kohli 2021). Moreover, there is significant evidence that the financial contributions from Tiger Conservation Foundations are being meaningfully reinvested into conservation efforts in Tiger Reserves. However, India's policy emphasis on ease of business and accelerated environmental clearances risks undermining these crucial conservation legislations. The Ministry of Environment, Forests and Climate Change has been progressively streamlining the public hearing and impact assessment requirements for development projects, ostensibly to cut red tape (Kumar 2020). However, conservation scientists warn that such deregulation seriously jeopardizes ecologically fragile areas, protected zones, and biodiversity-rich community lands by 'fast-tracking' linear infrastructure, mining, and power sector investments (Bindra 2020). The surreptitious introduction of the Environmental Impact Assessment Draft Notification 2020 during a pandemic lockdown, attempting to exempt a slew of destructive industries from environmental scrutiny, exemplifies this official impulse towards 'developmental nationalism' at odds with conservation imperatives.

Glaringly absent from the policy landscape are dedicated legal instruments for conserving neglected ecosystems and taxa that cumulatively represent the bulk of India's biodiversity. Inland freshwater systems nurturing exceptional native fish, amphibian, reptile, and invertebrate diversity are particularly under-represented in Protected Area networks, environmental impact regulations, and conservation funding priorities (Sarkar et al. 2021; Raghavan et al. 2013). The Wetlands (Conservation and Management) Rules 2017 are the sole national-level legislation for protecting natural wetlands, but lack teeth in checking anthropogenic threats (Dandekar and Thakkar 2020). Similarly, grasslands and other non-forest biomes vital for endemic dryland species are frequently mislabeled as 'wastelands' open to commercial exploitation (Rawat and Adhikari 2015). Marine conservation too remains piecemeal, targeting select charismatic species through sanctuaries and national parks, but lacking holistic seascape-based management (Bijoor et al. 2018).

Beyond ecosystem-specific policy gaps, India's conservation governance suffers from systemic coordination failures and capacity constraints. Jurisdictional overlaps between central, state, and local authorities alongside poor cross-departmental communication

routinely stymie integrated planning across terrestrial, freshwater, and marine realms (Karanth and Kudalkar 2017). Moreover, Panchayati Raj institutions empowered by the 73rd Constitutional Amendment to manage natural resources at decentralized scales are seldom recognized as legitimate conservation partners (Pathak Broome et al. 2021). Most wildlife policies still rely on insular techno-managerial approaches, paying lip service to community participation, access rights, and co-management without genuine power-sharing (Ghate 2021; Lele and Srinivasan 2013).

The heavily under-resourced, under-staffed and under-equipped state of frontline conservation agencies further paralyzes effective enforcement. India has among the world's highest rates of forest guard assaults and mortality, with one guard killed every 4 days on average (PTI 2020). Wildlife cybercrime too has emerged as a burgeoning challenge, exploiting enforcement loopholes to illegally trade exotic species over social media and e-commerce platforms. Yet, investments in strengthening field patrolling, surveillance technologies, wildlife forensics, and cyber-policing remain meager (Menon and Lavigne 2006; Gubbi et al. 2017). This sorry state of affairs is a far cry from the cutting-edge tools and training envisioned in various Plans and policy pronouncements.

Finally, India's conservation policies have consistently failed to catalyze mass citizen mobilization on the lines of air pollution or climate action. This lack of a broad-based environmental constituency is partly attributable to the narrow framing of biodiversity as a niche elite concern divorced from daily lives. Most policies adopt a simplistic 'awareness raising' approach rather than nurturing lasting 'connections' between humans and nature through cultural festivals, local knowledge, spiritual practices, and experiential learning (Athreya and Karanth 2012; Kanagavel et al. 2013; Kumar et al. 2013). Moreover, conservation discourses have historically pitted local livelihoods against wildlife, alienating the very communities who have long symbiotically coexisted with nature (Sahgal and Scarlott 2012). Building truly inclusive conservation coalitions thus demands a fundamental shift in mindsets, vocabularies, and engagement strategies.

Discussion

India's conservation efforts exhibit both successes and challenges when compared with other countries. For instance, India's tiger conservation efforts under Project Tiger have been globally lauded, resulting in a significant increase in tiger populations. This contrasts with countries like Indonesia, where tiger populations continue to decline despite conservation efforts due to habitat loss and poaching (Linkie et al. 2018).

Similarly, India's initiative to expand its protected area network mirrors efforts seen in Brazil's Amazon region. However, unlike Brazil, where deforestation rates have surged recently due to policy rollbacks, India has maintained relatively stable forest cover through stringent forest laws and community involvement in forest management (Chaturvedi 2023).

In terms of community-based conservation, India's models such as the Joint Forest Management (JFM) program have parallels in Kenya's community conservancies. Both countries have leveraged local community participation to achieve conservation goals, although Kenya's model has often been more financially sustainable due to significant ecotourism revenues (Glew et al. 2010).

However, India faces unique challenges in balancing rapid economic development with biodiversity conservation, a dilemma also seen in China. Both countries have undertaken massive infrastructure projects that threaten biodiversity, but China's ambitious ecological

civilization framework aims to integrate environmental goals with economic policies more comprehensively than India has managed so far (Zhang et al. 2020).

The detailed comparison underscores the need for India to enhance its policy implementation frameworks, improve cross-sectoral coordination, and foster greater community engagement to achieve conservation outcomes comparable to global best practices.

This national-scale assessment reveals intensifying extinction risks threats across taxa and habitats in India, despite several high-profile conservation schemes. While certain mammalian and avian species have turned a hopeful corner because of sustained legal protections, less visible organisms like amphibians, freshwater fish, reptiles, invertebrates and plants exhibit alarming endangerment escalations. Such findings concur with global meta-analyses documenting greater recovery prospects for appealing, sentimentally valued species that disproportionately attract conservation funding relative to less charismatic biota (Brooke et al. 2014). However, the latter collectively constitute crucial ecosystem engineers like seed dispersers, soil builders, nutrient cyclers and pollinators whose continued decline gravely imperils vital life-support processes (Sekercioglu 2012; Balvanera et al. 2016). Therefore balancing emotional, utilitarian and ethical imperatives within conservation necessitates judiciously apportioning resources across overlooked species even if visually less captivating (Jepson and Barua 2015; Jarić et al. 2019).

Nationally, persisting biodiversity threats signal sizable implementation gaps impeding policy efficacy and impacts on the ground. Although India boasts one of the oldest wildlife protection regimes globally, associated gains remain confined to demarcated Protected Areas covering under just 5% of total land. Ambitiously expanding this estate as originally envisaged under the 2002 Biological Diversity Act could enhance species representation and viability. However financial, land acquisition and opportunity costs may prove exorbitant if exclusionary fortress conservation models get further entrenched (Shahabuddin and Bhamidipati 2014; Brockington and Wilkie 2015). Instead, our findings advocate an interconnected mosaic vision integrating Protected Areas as ecological anchors within multifunctional working landscapes supporting both conservation and human usage (Phalan et al. 2011; Reed et al. 2017).

In addition to assessing the overall extinction risk trends, it is crucial to consider the distribution of these species across various Protected Areas (PAs) in India. The decline of species within and outside PAs highlights the significance of these areas in conserving biodiversity. By analyzing the decline levels at the PA level, we can better understand the effectiveness of different categories of PAs, such as National Parks, Wildlife Sanctuaries, and Biosphere Reserves, in protecting these species. This approach underscores the need for targeted conservation strategies within PAs to mitigate the ongoing decline of biodiversity.

Globally such reconciliation approaches are gaining traction under frameworks like shared socioeconomic pathways, nature's contributions to people and the ecosystem services perspective (Raudsepp-Hearne and Peterson 2020; Díaz et al. 2019; Raudsepp-Hearne et al. 2020). These formulations explicitly acknowledge that human quality of life derives from properly functioning socio-ecological systems necessitating integrated governance mindful of nature-society interlinkages (Díaz et al. 2019; Mastrángelo et al. 2019; Pascual et al. 2017). By foregrounding biodiversity considerations within public policies on agriculture, urban development, water management and industrial growth, significant sustainability gains become feasible without severely curtailing economic advancement (Kok et al. 2018; Leclère et al. 2020). Our gap analysis and interview insights strongly reinforce this message while cautioning against pursing environmental policies in seclusion.

Instead, what emerges is an urgent need to transition prevailing governance modalities from compartmentalized technocratic interventions towards networked, participatory

decision-architectures well attuned to realities on the ground and in the water. This redirection entails embracing complexity rather than seeking illusory control, dynamic novelty over rigid equilibrium and humble adaptiveness over hubristic optimization pretensions (Allen et al. 2017; Ostrom 2009; Holling 2001). Concrete steps like integrating village councils and youth collectives within nationwide biodiversity monitoring (Gadgil 2021), leveraging corporate social responsibility mandates for habitat restoration (Aggarwal 2014), and formally Capturing indigenous knowledge (Berkes 2017) could spur such systemic reorganization. Overall, a fundamental philosophical shift appears imperative eschewing atomized initiatives to nurture flexible, context-specific conservation pathways aligned with India's cultural ethos and developmental ambitions.

Future directions for conservation priorities in India

India's biodiversity conservation efforts are at a critical juncture, necessitating a forward-looking approach that aligns with both national and global sustainability goals. While existing frameworks have laid the groundwork for conservation, there is an urgent need to implement actionable strategies that are both implementable and quantifiable. The following policy-level recommendations are proposed to enhance conservation outcomes:

Integrated landscape management

- Policy Recommendation: Develop and implement landscape-level conservation plans that integrate protected areas with surrounding land uses, ensuring ecological connectivity and sustainable resource management.
- Implementation Strategy: Establish regional conservation councils that include stakeholders from government, local communities, and industry to coordinate land-use planning and conservation efforts.

Strengthening community-based conservation

- Policy Recommendation: Empower local communities through co-management agreements and financial incentives to steward biodiversity in their regions.
- Implementation Strategy: Expand community forestry and fisheries programs, providing technical support and access to markets for sustainable products.

Enhancing invasive species management

- Policy Recommendation: Establish a national task force dedicated to early detection, control, and eradication of invasive species.
- Implementation Strategy: Implement regular monitoring programs using citizen science initiatives and provide funding for research on biocontrol methods.

Pollution control and habitat restoration

- Policy Recommendation: Enforce stricter pollution controls and initiate large-scale habitat restoration projects, particularly in degraded freshwater and coastal ecosystems.

- Implementation Strategy: Utilize public–private partnerships to finance restoration efforts and leverage technology for real-time pollution monitoring.

Promoting agro-ecological transitions

- Policy Recommendation: Support the transition to sustainable agricultural practices that protect biodiversity and enhance ecosystem services.
- Implementation Strategy: Implement subsidy programs for farmers adopting organic farming, agroforestry, and conservation agriculture techniques.

Strengthening legal frameworks and enforcement

- Policy Recommendation: Amend existing environmental laws to include clear mandates for biodiversity conservation and ecosystem service valuation.
- Implementation Strategy: Increase funding for enforcement agencies and integrate technology such as drones and satellite imagery to monitor compliance.

Fostering research and innovation

- Policy Recommendation: Invest in research and development to advance conservation science and technology.
- Implementation Strategy: Create innovation hubs that bring together academia, government, and private sector to collaborate on conservation challenges.

Monitoring and evaluation

- Policy Recommendation: Develop a robust framework for monitoring and evaluating the effectiveness of conservation policies and programs.
- Implementation Strategy: Establish a national biodiversity monitoring system that incorporates both scientific and traditional knowledge systems.

These recommendations, grounded in the findings of this study, aim to provide a comprehensive roadmap for conserving India's rich biodiversity while meeting the socio-economic needs of its population. Implementing these strategies will require collaboration across sectors and scales, ensuring that conservation becomes an integral part of India's development paradigm.

Conclusion

Our national-scale assessment reveals a pattern of increasing extinction risk across multiple taxonomic groups over recent decades. However, it is important to acknowledge several significant conservation successes. Additionally, we have included comparisons of Indian conservation scenarios with successful and challenging scenarios in other countries in the discussion section. However, observed conservation gains remain relatively muted beyond a few legally protected species like tigers, elephants, and eagles. Our research therefore highlights sizable implementation gaps impeding translation

of admirable de jure mandates into demonstrable de facto outcomes. Tackling this efficacy deficit demands fundamental governance realignments embracing participatory decision-making, cross-sector coordination, community stewardship models and green infrastructural integration within everyday public policies.

Building on these insights, we propose priority strategic investments spanning invasives control, ecological restoration, sustainability transitions, monitoring improvements and access-benefit sharing streamlining. Successful realization of India's conservation targets ultimately hinges on this balanced, context-attuned approach attentive to equity and sustainability concerns during development planning. With conscientious political commitment and multi-stakeholder participation, significant biodiversity gains become eminently feasible without undermining socio-economic aspirations. Conserving India's staggering biotic heritage is thus not a luxury but an existential necessity—for the well-being of current and future generations.

We recognize that our analysis is inherently limited by the taxa, criteria and spatial units used to assess extinction risks and policy impacts. Groups like fungi, lichens, insects, and soil fauna vital to ecosystem functioning are entirely missing from our review owing to data constraints. Our priority recommendations too are necessarily generic, warranting further place-based socio-political calibration to address India's unique federal, multi-cultural context. Nevertheless, the clear indications of conservation shortfalls revealed through our integrated species-policy-investment analysis provide a crucial evidence-base for orienting strategic course corrections.

Several promising areas for future research emerge from our findings. Comparative political analyses of successful biodiversity legislations can generate instructive lessons on coalition building, public mobilization, and strategic litigation. Modeling studies that quantify ecosystem service co-benefits can bolster the economic case for biodiversity interventions. Psychological investigations into the drivers of pro-conservation behaviors can inform targeted messaging campaigns and policy nudges. Embedding such multi-disciplinary insights within a plural epistemological framework spanning natural and social sciences, traditional knowledge and citizen inputs offers a holistic template for re-imagining conservation practice and policy in India.

Appendix 1

Species-level extinction risk trends disaggregated by major taxonomic groups.

Taxonomic Group	% Threatened at First Assessment	% Threatened in Latest 2022 Assessment
Amphibians (n = 250)	5.2	38.6
Mammals (n = 423)	14.7%	25.3
Birds (n = 1172)	3.2	12.5
Reptiles (n = 260)	4.2	10.6
Actinopterygii (n = 223)	5.1	21.5
Anthozoans (n = 240)	8.6	32.5
Gastropods (n = 91)	4.4	30.8
Odonates (n = 60)	2.1	8.4

Taxonomic Group	% Threatened at First Assessment	% Threatened in Latest 2022 Assessment
Plants (n = 40)	1.8	7.3

Appendix 2

Species-level extinction risk trends disaggregated by biodiversity hotspot regions.

Biodiversity Hotspot	Region	% Threatened at First Assessment	% Threatened in Latest 2022 Assessment
Western Ghats & West Coast (n = 1182)	Overall	6.2	23.7
	Plants	12.5	67.2
	Amphibians	17.8	59.3
	Freshwater Fish	11.2	42.0
	Odonates	3.4	18.6
	Reptiles	7.9	26.4
North-East India (n = 927)	Overall	6.7	22.4
	Mammals	18.5	37.6
	Birds	4.9	18.7
	Reptiles	5.2	16.5
	Amphibians	11.3	42.2
	Freshwater Fish	7.6	35.8
Andaman & Nicobar Islands (n = 253)	Overall	9.3	29.6
	Plants	5.8	17.4
	Birds	11.2	23.6
	Mammals	23.1	53.8
	Reptiles	16.7	41.7
	Amphibians	33.3	66.7

Glossary

1. Invasive species control	Alien invasive plants, mammals and reptiles severely endangernative biota across habitats. Potential interventions include import restrictions, early detectionvia monitoring, mechanical/chemical control and biocontrol research.
2. Ecological restoration	Habitat degradation is pervasive with Protected Areas alsoimpacted. Restoration through native plantations, managed natural regeneration andhydrological revitalization can accelerate recovery.

3. Agro-ecological transitions	Agricultural intensification critically threatens endemicdryland biota and wetland ecosystems via chemical effluents and desertification. Stateadvisory services should actively incentivize minimum tillage, organic farming, mixedcropping, conservation agriculture and agroforestry.
4. Pollution abatement	Industrial effluents and untreated urban sewage have created overly polluted waterways hostile to intrinsic biota while fostering invasive species. Command-and-control restrictions coupled with compliance assistance programs are essential to control contamination at source.
5. Ecological connectivity	Linear infrastructure like roads and canals severely fragmentshabitats driving population isolation and gene flow disruption. Strategic mitigation viawildlife underpasses and overpasses aligned with identified dispersal corridors can re-connecthabitats for improved viability.
6. Community-based adaptation	Revitalizing community forest rights, customary tenure and co-management institutions supports self-organized stewardship attuned to local socio-ecological feedbacks. This culturally resonant model cost-effectively safeguards ecosystem health and local livelihoods simultaneously.
7. Access and benefit sharing streamlining	Indigenous communities possess invaluablemedicinal plant knowledge but lack recognized stakes in commercial applicationsundermining conservation incentives. Clarifying administrative procedures for bioprospectingpatents, licensing and royalty flows offers a potential solution.
8. Green infrastructure integration	Complementing the existing built fabric with greenelements like urban wetlands, peri-urban woodlots and mangrove buffers amplifies habitatextent while delivering air/water quality co-benefits to human settlements.
9. Sustainability transitions	Pursuing sustainable transitions across energy, mobility andagricultural sectors will require judiciously balancing ecological impacts against developmentgains through appropriate regulatory frameworks.
10. Monitoring and enforcement	Expanding nationwide biodiversity surveillance throughcitizen science platforms and remote sensing coupled with stronger enforcement mechanismscan improve compliance and accountability across policies.

Collectively these ten interventions constitute targeted, evidence-driven conservationinvestments closely aligned with India's unique socio-cultural milieu and sustainabilitychallenges.

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