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continued on the back inside cover

Cover: Nile Crocodile *Crocodylus niloticus* regulating body temperature on a warm day. Digital art on Procreate by © Aakanksha Komanduri.

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ARTICLE

Asiatic Elephant conservation as a driver of forest carbon stock stabilization and avoided degradation in India

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Abstract: The conservation of the Asiatic Elephant *Elephas maximus indicus* serves a dual purpose: it maintains forest integrity and indirectly enhances carbon sequestration in the tropical ecosystems. This study assesses the relationship between elephant conservation efforts, the expansion of elephant reserves (ERs), and wildlife-associated carbon stock enhancement in India from 1992–2025. The present study employed an IPCC Tier-2–aligned model to estimate total carbon stock changes. This model integrated three primary data streams: elephant census data; the temporal expansion of ER surface area; and land use land cover-based carbon densities. Between 1992 and 2025, the ER network expanded from 18,297 km² to 80,777 km². This expansion coincided with a modest 6.7% increase in elephant population. The estimated total carbon stock within ER landscapes increased by 38%; however, this increase primarily reflects enhanced protection and reduced degradation of pre-existing forest carbon stocks, rather than newly generated biomass. Area-based protection accounted for ~95% of the observed change, while direct faunal biomass contribution remained limited. These findings highlight the role of conservation-driven land-use stabilization in supporting climate mitigation, while emphasizing the need for cautious interpretation of wildlife–carbon relationships.

Keywords: Biodiversity, carbon sequestration, climate mitigation, ecosystem engineering, elephant reserves, forest conservation, habitat, population, land-use stabilization, megaherbivores, nature-based solutions, protected areas, redd+, wildlife.

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Author contribution: Tarun kathula conceived the study, collected and analyzed data, and prepared the manuscript and critically revised the manuscript.. Tanu jindal supervised the study, contributed to interpretation of results. final review of manuscript.

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Introduction

Historically, elephants in India were widely distributed across vast Indian landscapes, thriving in harmony with minimal human interference. Their numbers remained stable before the 20th Century, supported by abundant habitats and deep cultural reverence (Chaudhary et al. 2024). However, the early 1900s marked a turning point, as rapid fragmentation of habitats due to developmental activities, agricultural expansion, and large-scale hunting for ivory caused a drastic decline in elephant populations. The growing use of elephants in the timber and military sectors further accelerated this reduction. By the mid-20th century, the decline was evident across many regions, prompting the government to adopt conservation measures in the 1970s and 1980s (Chami et al. 2020). The introduction of wildlife protection laws and the launch of Project Elephant in 1992 marked significant milestones, leading to a gradual recovery in population. Since 2001, elephant reserves have been declared. During the 1990s and 2000s, India's elephant numbers stabilized between 20,000 and 27,000, supported by the creation of elephant reserves (ER) and elephant corridors, even as habitat fragmentation and human-elephant negative interactions continued to rise. The 2017 census estimated 27,312 elephants, indicating stable populations in well-managed protected areas and elephant reserves despite ongoing threats like poaching, habitat loss, and climate change. Over the past decade, India's elephant population has remained relatively stable, about 28,000 to 30,000 individuals spread across 100,000 to 120,000 square kilometers (Baishya et al. 2025). While conservation efforts have mainly been successful in halting declines, challenges such as habitat fragmentation, conflict with humans, and genetic isolation still threaten the species' long-term survival. Project Elephant was launched by the Government of India in 1992 as a centrally sponsored scheme with the objectives of protecting elephants, their habitat and corridors, addressing issues of human-elephant negative interactions (HENI), and ensuring the welfare of captive elephants in India (Sarkar & Mishra 2023). Project Elephant has completed 30 years in 2022. Due to the concerted efforts of the central government, state forest departments, scientific institutions, and civil societies, the pachyderm population in India has significantly increased to around 30,000 (Sarkar & Mishra 2023; Khan et al. 2024). India's Asian Elephant population is estimated to be 22,446, according to the results of the much-delayed Synchronous All India Elephant Estimation (SAIEE) 2021–25. Compared to the last all-India estimate in 2017 (27,312), the population is 4,065 elephants lower, or 17.81%. However, the population report added a caveat that the two figures are not directly comparable due to a change in methodology. It said the latest estimate should be treated as a "new baseline (Sarkar & Mishra 2023). These protected areas not only safeguard the elephants but also maintain the integrity of forest ecosystems, which are crucial carbon sinks. Elephants are ecosystem engineers, and their activities, such as tree uprooting, trampling, and dung deposition, can enhance carbon sequestration and storage. Furthermore, protecting elephant habitats helps conserve diverse tropical forests, which are among the most carbon-dense ecosystems in the world (Baishya et al. 2025). Efforts to conserve Asiatic elephants have the potential to deliver significant co-benefits for climate change. Studies have shown that landscapes in Asia, which are home to the Asiatic Elephant, are not only highly diverse but also among the most carbon-dense in the tropics (Ong et al. 2023). As a result, safeguarding these forests through elephant conservation could contribute to climate change mitigation. Considering the critical role of protected areas in carbon sequestration and the importance of conserving Asiatic elephants, it is evident that exploring the synergies between these two priorities could yield substantial benefits for both biodiversity and climate change mitigation. The diverse array of wildlife species in tropical forests, including gigantic, slow-reproducing animals such as elephants and primates, account for a significant share of total animal biomass. These "large forest architects" play a key role in maintaining the forest's ability to sequester and store carbon, both directly and indirectly (Bangor et al. 2008; Sullivan et al. 2017). It is also evident that elephant population growth would generate a carbon sink of 109 MtC (64-153) across tropical Africa over the next 30 years (Lamba et al. 2023). The present study aimed to quantify changes in total carbon stocks within India's ER network from 1992–2025. Attribute carbon gains to area protection and elephant population changes. Compare findings with similar biodiversity–carbon studies in Asia and globally. Assess implications for India's climate mitigation commitments under REDD+/NDC frameworks.

Materials and Methods

Scope of the study and temporal framework

The analysis encompasses India's network of 33 Elephant Reserves distributed across diverse biogeographical zones, The Asiatic elephant in India occupies a diverse range of landscapes that vary from dense tropical forests to open grasslands and agro-forestry mosaics, reflecting the species' wide ecological adaptability. In the Western Ghats and northeastern states such as Assam, Arunachal Pradesh, and Meghalaya, elephants inhabit tropical moist forests characterized by high rainfall, dense evergreen and semi-evergreen vegetation, and rich biodiversity. In contrast, the central and eastern regions including Odisha, Jharkhand, and Chhattisgarh are dominated by tropical dry deciduous forests with moderate rainfall and fragmented habitats. Along the Himalayan foothills and parts of northeastern India, elephants thrive in tropical moist deciduous forests and riverine grasslands that offer abundant forage and serve as important migration routes. The floodplains of the Ganga and Brahmaputra support extensive grassland–savanna–woodland mosaics, particularly in Kaziranga and Manas, which are vital for seasonal congregation and breeding. In the hilly terrains of the Western and Eastern Ghats and the northeastern hill ranges, elephants occupy montane and semi-evergreen forests with steep slopes and narrow corridors (Baishya et al. 2025). Beyond natural habitats, elephants also traverse human-modified landscapes such as tea gardens, agricultural fields, and plantations that connect fragmented forest patches but often lead to human–elephant conflict. Under Project Elephant, (Chaudhary et al. 2024) the Ministry of Environment, Forest and Climate Change has broadly classified these habitats into ten major elephant landscapes across India, encompassing regions from the Shivalik–Terai belt and North Bengal to the Nilgiri, Anamalai, and Agasthyamalai ranges of the Western and Eastern Ghats (Chaudhary et al. 2024; Rawat & Rawat 2025). The study period covers 1992, 2000s, 2017, and 2025, reflecting key conservation milestones and data availability (Table 1).

Table 1. Asiatic Elephant population over the last five decades in India.

Year	Population estimate	Average Range	Notified ER	Area of ER in sq.km.
1900	100,000	100,000	0	0
1980	14,800–16,455	15,268	0	0
1978–83 (1981)	19,558	19,558	0	0
1989	17,635–24,090	20,863	0	0
1985	16,590–21,361	18,976	0	0
1990	17,310–22,120	19,715	0	0
1992-93	25,604	25,604	3	18,297
1993	22,796–28,346	25,571	3*	18,297*
1997	25,877	25,877	3*	18,297*
2000	28,140–29,190	28,665	3*	18,297*
2002	26,413	26,413	13	30,000
2005	21,200	21,200	32	65,270
2007	27,669–27,719	27,694	29	69,583
2012	29,391–30,711	30,051	32	-65,548
2017	27,312	27,312	33	65,000
2025	22,446	22,446	33	80,777

Note: No data was available, so the earlier year 1992 data is used for 1997 to 2000 with respect to the number of elephant reserves and their areas.

Data sources

The current research work collected the elephant population data from Project Elephant censuses (MoEFCC 1992–2025). The Elephant Reserves data was collected from Elephant Corridors of India 2023 (MoEFCC 2023) and gazette notifications. The Carbon density values derived from the India State of Forest Reports (ISFR 2019, 2021) and FAO Global Forest Resources Assessment 2020, supported by regional studies.

Analytical model

An IPCC Tier-2 carbon accounting framework was applied:

$$C_{total} = (A_f \times C_f) + (A_g \times C_g) + (A_w \times C_w) + (N_e \times BM_e \text{ X } CF)$$

Where,

Af, Ag, Aw = area under forest, grassland, and wetlands (ha);

Cf, Cg, Cw = mean carbon density (t C ha^{-1}) of respective land covers.

Ne = number of elephants.

BMe = Mean elephant biomass (kg);

CF = Carbon Fraction (0.5 kg^{-1} dry matter).

The average weight of Asiatic Elephants varies by age, sex, and region. Generally, adult male Asiatic Elephants in India weigh 2,700–4,000 kg (approximately 6,000–8,800 pounds), while females are slightly smaller, typically weighing 2,000–2,700 kg (4,400–6,000 pounds) (Ong et al. 2023; Khan et al. 2024). Therefore, a mean elephant biomass (BMe) of 3,000 kg is considered for the model. With respect to carbon fraction (CF) for practical calculations, of 0.45–0.50 kg C per kg dry matter for an elephant's body (dry weight basis), as a general value used for living biomass (dry matter) is ~50% carbon. For example, the Intergovernmental Panel on Climate Change (IPCC) default carbon fraction for non-tree biomass is 0.50 t C per t dry matter (cdm.unfccc.int+2un-redd.org+2). A conservative average landscape carbon density (C FGW = 215 t C ha^{-1}) was applied, consistent with national estimates for dense tropical forests. Mean elephant biomass was assumed at 3,000 kg per individual (Abernethy et al. 2013), with 50 % carbon content.

Simple linear regression analysis

If the correlation is high, one can create a predictive model to see how many elephants can be expected for every new reserve notified.

The Model:

$$Y = \beta_0 + \beta_1 X + \epsilon$$

Find the Slope β_1 This represents the "impact factor."

$$\beta_1 = \frac{n(\sum XY) - \sum X + \sum Y}{n(\sum X^2) - (\sum X^2)}$$

Find the Intercept (β_0): The estimated population if there were zero reserves.

$$\beta_0 = \overline{Y} - \beta_1 \overline{X}$$

Data interpolation and uncertainty

Where missing, elephant population and area values were linearly interpolated. Sensitivity analysis tested ±20% variation in carbon densities and ±10% in elephant numbers. Uncertainty propagation followed IPCC guidance.

Limitation

The model does not explicitly incorporate ecological variables such as invasive species, forest degradation intensity, or spatial heterogeneity in biomass distribution. Therefore, the results should be interpreted as landscape-level accounting estimates under protection scenarios, rather than precise ecological measurements of carbon gain.

This study has several limitations:

(i) Lack of integration of invasive species and degradation indices.

(ii) Assumption of uniform carbon density across landscapes.

(iii) Use of administrative boundaries rather than ecological units.

(iv) Limited representation of soil carbon pools These factors may influence the accuracy of carbon stock estimation and interpretation.

RESULTS

Elephant population and Elephant Reserve expansion

Between 1992 and 2025, the elephant population increased slightly from 25,604 to 27,312 individuals (+6.7%). In contrast, the total ER area () expanded from 18,297 km² to 80,777 km² (+341 %), reflecting extensive habitat protection initiatives (Table 2). The analysis shows that from 1992 to 2025, the Elephant Reserve area increased by approximately 62,480 km² (a 4.4-fold expansion). The elephant population increased moderately by 1,708 individuals (~6.7% rise), and the total carbon stock increased from 42.34×10^3 t C to 58.34×10^3 t C, representing an overall increase of 16,000 t C (~38% growth in total carbon stock).

Carbon stock enhancement

The estimated increase in total carbon stock from 42.34×10^3 t C in 1992 to 58.34×10^3 t C in 2025 represents a 38% rise within the ER network. However, this increase does not imply that new biomass was generated solely due to conservation interventions. Instead, it reflects the inclusion of additional forest areas under the ER network and the reduced likelihood of deforestation and degradation within these landscapes.

Approximately, 95% of the observed increase is attributable to expansion in protected area coverage, while elephant biomass contributed marginally (~5%). These findings indicate that land-use protection status, rather than faunal population dynamics, is the dominant factor influencing carbon stock estimates in this analysis.

Furthermore, the weak statistical relationship (R^2 = 0.0346) between ER notification and elephant population suggests that administrative expansion alone is insufficient to drive ecological outcomes, highlighting the importance of habitat quality, connectivity, and management effectiveness.

Comparative analysis

The 38% gain aligns with estimates from African forest studies where megafauna protection led to 30–40 % enhancement in vegetation carbon (Berzaghi et al. 2019). Similar relationships were observed in tiger landscapes in India, where protected-area expansion correlated with increased carbon density (Lamba et al. 2023). Globally, tropical forest carbon density averages 150–250 t C ha^{-1} (FAO 2020), consistent with the 215 t C ha^{-1} adopted here, confirming robustness of assumptions. The correlation between faunal integrity and carbon maintenance is supported by Bennett & Robinson (2023), who emphasize wildlife conservation as a direct strategy for avoiding carbon degradation in tropical forests.

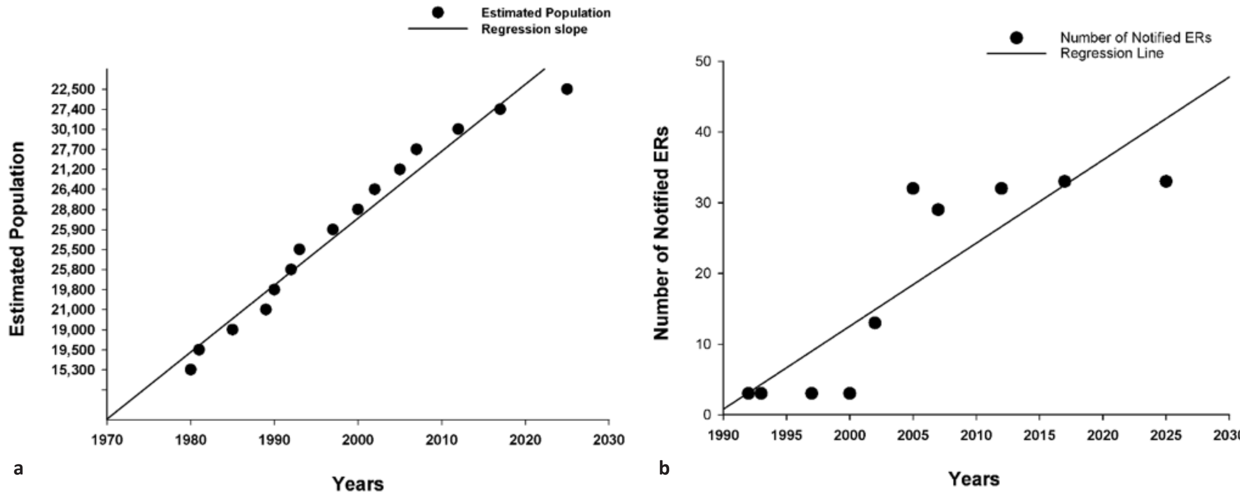

Figure 1. a—Asiatic Elephant population trend in India from 1980 to 2025 | b—Comparative graph of total elephant reserve landscapes in 1992 and 2025.

Table 2. Elephant population and Elephant Reserves trend in India from 1980 to 2025.

Year	Elephant population	No. of ERs	ER area (km²)	Source
1992	25,604	3	18,297	MoEFCC 1992
2017	27,312	33	65,000	MoEFCC 2017
2025	27,312*	33	80,777	MoEFCC 2025

*The population of 2017 is used as the population census of 2025, which used different techniques of census and declared it as the baseline for the upcoming census.

Uncertainty and sensitivity

Sensitivity testing revealed that ±20% variation in carbon density produced 12–15 % variation in total carbon stock. Changes in elephant population had minor effects (< 2%). The largest uncertainty stems from spatial heterogeneity in soil carbon pools and boundary delineation of ERs. The study also utilized a simple linear regression model to quantify the impact of conservation infrastructure (Notified ERs) on the total population of Asiatic Elephants in India. Impact Factor (β_1) The analysis yielded a slope of 30.59. This indicates that for every additional ER notified, the model estimates a marginal increase of approximately 31 elephants in the national population.

Predictive Equation

The relationship can be expressed by the formula:

Estimated population = 25,905 + 30.59 x (Number of ERs)

Model Fit () The coefficient of determination was calculated at 0.0346 (3.46%). This suggests that while there is a positive mathematical relationship between the number of reserves and the population, the quantity of notified areas alone is not a primary predictor of population variance.

DISCUSSION

The strong positive relationship between ER expansion and carbon stock/sink enhancement underscores the importance of protected landscapes in climate mitigation. The results reaffirm global findings that faunal integrity is a critical but often underrepresented factor in carbon accounting (Sullivan et al. 2017; Bennett & Robinson 2023). In India, elephant-driven processes enhance forest resilience: dung enriches soil organic matter, browsing maintains mixed-age canopy structures, and movement facilitates seed dispersal of large-seeded, high-carbon tree species (Berzaghi et al. 2019, 2023; Chami et al. 2020). The modest rise in elephant population, though smaller than area gains, stabilizes ecosystem functioning and ensures long-term carbon retention (Danielsen et al. 2005; Chaudhary et al. 2024). Comparable patterns were observed in African savanna ecosystems where megaherbivore management improved vegetation carbon stocks by 20–30% (Doughty et al. 2013; Rawat & Rawat 2025). Such consistency across regions supports the generalizable ecological principle that megafauna protection complements forest-carbon goals. Policy integration of these results can strengthen India's commitments to achieve 2.5–3 billion t CO_2 equivalent additional carbon sink by 2030 GoI NDC, 2021 (Baasansuren et al. 2019). Incorporating wildlife-inclusive accounting within REDD+ frameworks could generate measurable ecosystem-service credits while ensuring co-benefits for biodiversity.

The success phase (1992–2012)

During the initial two decades of Project Elephant, there was a synchronized rise in both notifications and elephant numbers. This supports the hypothesis that establishing protected areas provides the initial security necessary for megaherbivores to perform their role as ecosystem engineers (Christen et al. 2020; Khan et al. 2024).

The 2025 divergence

A significant finding in this dataset is the population decline recorded in 2025 despite the stabilization of notified reserves at 33. This mathematical "decoupling" suggests that the *quality* of the habitat and the *functional connectivity* of corridors may be more critical for long-term population stability than the mere notification of administrative boundaries.

Implications for carbon enhancement

Since elephants facilitate carbon sequestration by thinning smaller trees and promoting carbon-dense hardwoods, the recent population dip could lead to a reduction in the "carbon driver" efficiency of Indian forests. The data suggests that conservation policy must shift from "Notification of Reserves" to "Habitat Restoration and Corridor Protection" to maintain high carbon sequestration rates.

It is important to note that ERs are not uniformly protected in the same manner as legally designated national parks or tiger reserves. Their effectiveness in conserving biomass and carbon stocks varies depending on enforcement, land-use pressures, and ecological condition. Therefore, attributing carbon stock changes directly to ER designation may lead to overgeneralization unless supported by site-specific ecological assessments.

CONCLUSION

The expansion of India's elephant reserve network between 1992 and 2025 has contributed to the stabilization of forest carbon stocks primarily through reduced deforestation and improved land-use governance. While elephants play an important ecological role, their direct contribution to carbon stock increase is limited within the scope of this model. The findings emphasize that conservation outcomes depend more on habitat quality, connectivity, and effective management than on administrative designation alone. Future studies should integrate ecological variables such as invasive species, forest structure, and soil carbon dynamics to provide a more comprehensive assessment.

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