Ecosystem Integrity in Bhutan's Protected Area Network: A Spatial Assessment Using the Ecosystem Integrity Index

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Abstract

Monitoring ecosystem integrity across protected-area networks is central to meeting the Kunming–Montreal Global Biodiversity Framework (KM-GBF) Target 3 commitment to conserve 30% of Earth's land by 2030, yet standardized national-scale assessments remain scarce in mountain biodiversity hotspots. We applied the globally standardized Ecosystem Integrity Index (EII) to all 19 protected areas and biological corridors in Bhutan's Eastern Himalayan network, covering 19,750 km² at 300-m resolution using Google Earth Engine. The network-wide area-weighted mean EII was 0.679 (SD = 0.102), with individual protected-area means ranging from 0.476 to 0.821; 14 of 19 protected areas (89.6% of total network area) maintained mean EII values above 0.60. Structural and compositional integrity were consistently high (means >0.950), whereas functional integrity showed greater spatial heterogeneity (mean = 0.655). Biological corridors exhibited the widest integrity range among all protected-area categories, spanning nearly the full network range (0.478–0.821), with direct implications for landscape connectivity management. Counterfactual comparisons indicated that 13 of 19 protected areas exhibited higher integrity inside their boundaries, while elevation (61.800%) and human modification (20.700%) dominated spatial variation. These findings demonstrate how standardized integrity metrics can operationalize KM-GBF Target 3 compliance monitoring, providing a transferable framework for data-limited mountain regions globally.

Keywords: counterfactual analysis; remote sensing; conservation effectiveness; mountain ecosystems

Introduction

Ecosystem integrity refers to the capacity of ecosystems to maintain their structure, composition, and functioning under anthropogenic and environmental pressures (Kandziora et al., 2013). The concept has gained prominence in international conservation policy, with the Kunming–Montreal Global Biodiversity Framework explicitly targeting the maintenance and restoration of ecosystem integrity (Convention on Biological Diversity [CBD], 2022). Operationalizing this concept for monitoring and evaluation requires spatially explicit indicators that can be applied consistently across large areas and repeated over time (Scholes & Biggs, 2005).

Advances in remote sensing have enabled global assessments of ecosystem condition and cumulative human pressures (Kennedy et al., 2019; Theobald et al., 2020). The Global Human Modification Index revealed that approximately 95% of Earth's terrestrial surface shows some degree of anthropogenic modification (Kennedy et al., 2019), while global forest-change products have documented habitat loss and fragmentation at unprecedented spatial and temporal resolution (Hansen et al., 2013). These developments have facilitated spatially explicit evaluations of protected-area performance, although such analyses remain constrained in data-limited regions.

Protected areas remain the cornerstone of global biodiversity conservation strategies (Geldmann et al., 2013). The target of conserving at least 30% of terrestrial and marine areas by 2030 further underscores reliance on area-based approaches (CBD, 2022). Nevertheless, evidence for protected-area effectiveness is mixed. A recent global analysis of more than 160,000 protected areas reported that, on average, protected sites were 33% more effective than unprotected areas at reducing habitat loss, but outcomes varied strongly with size, management regime, and regional context (Li et al., 2024). Meta-analyses have likewise documented positive biodiversity responses to protection at global scales but weaker or inconsistent effects in parts of the tropics (Cazalis et al., 2020). These patterns indicate the need for systematic, spatially explicit assessments of protected-area conditions using standardized metrics.

The Ecosystem Integrity Index (EII) offers a globally consistent framework for quantifying terrestrial ecosystem condition through integrated functional, structural, and compositional dimensions (Sun et al., 2026). Although the EII has informed global conservation prioritization, applications at national scales and within protected-area networks remain limited.

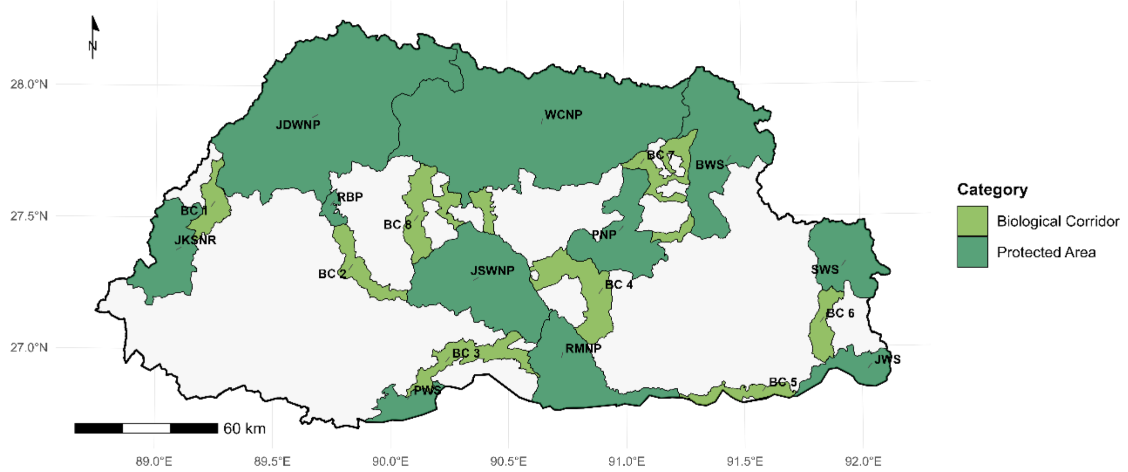
Bhutan provides a globally significant setting for ecosystem-integrity assessment. Located within the Eastern Himalayan biodiversity hotspot — one of the world's 36 biodiversity hotspots and among the richest in irreplaceable endemic species (Myers et al., 2000) — the country maintains approximately 52 % of its territory within a nationally connected protected-area system comprising five national parks, four wildlife sanctuaries, one strict nature reserve, and eight biological corridors (Royal Government of Bhutan, 2023). These corridors serve not only as national connectivity linkages but also as transboundary wildlife linkages between India's northeastern protected landscapes and the Tibetan Plateau, amplifying the international conservation significance of their ecological condition. The network spans elevational gradients from subtropical lowlands to alpine environments exceeding 7,000 m, capturing exceptional ecological heterogeneity. Previous research has documented conservation-relevant pressures in Bhutan, including human–wildlife conflict, livestock depredation by large carnivores, and localized habitat modification (Wang et al., 2006; Wang & Macdonald, 2006). More recent studies emphasize the importance of both protected and non-protected landscapes for sustaining wildlife populations and maintaining ecological connectivity (Choki et al., 2023; Dendup et al., 2021).

Despite the conservation significance of Bhutan's protected-area network, spatially explicit evaluations of ecosystem integrity across the full system remain absent. This gap is particularly urgent in the context of the KM-GBF, which requires signatory nations to demonstrate that their conserved areas are not only spatially extensive but effectively maintaining ecological condition — a standard that demands operational integrity metrics, not merely coverage statistics. We address this gap by applying the EII to all 19 protected areas in Bhutan to: (1) quantify overall and component-specific integrity patterns; (2) compare integrity among protected-area categories, with particular attention to biological corridors as nationally designated connectivity linkages; (3) evaluate inside–outside contrasts using counterfactual buffer analysis; and (4) identify environmental and anthropogenic correlates of spatial variation in integrity. In doing so, we provide the first national-scale test of EII-based monitoring as a tool for KM-GBF Target 3 compliance reporting in a Himalayan biodiversity hotspot and demonstrate a transferable analytical workflow applicable to comparable data-limited mountain regions globally.

Methods

Study area

The study encompassed Bhutan’s national protected-area network, comprising 19 protected areas with a combined area of 19,750.160 km² (Table 1). The system includes five national parks (Jigme Dorji Wangchuck National Park, Jigme Singye Wangchuck National Park, Phrumsengla National Park, Royal Manas National Park, and Wangchuck Centennial National Park), four wildlife sanctuaries (Bumdeling, Jomotsangkha, Phibsoo, and Sakteng), one strict nature reserve (Jigme Khesar Strict Nature Reserve), one botanical park (Royal Botanical Park), and eight biological corridors linking core protected areas (Fig. 1).



Source: Department of Forests and Park Services, Bhutan

Fig. 1 Map of the study area showing Bhutan’s protected area network and associated biological corridors. Map lines delineate study areas and do not necessarily depict accepted national boundaries

Protected-area boundaries were obtained from nationally curated spatial datasets maintained by government agencies and originally provided in the DRUKREF03 Transverse Mercator projection (EPSG:5266). For spatial analysis in Google Earth Engine, all boundaries were reprojected to the WGS84 geographic coordinate system (EPSG:4326). The national boundary of Bhutan was used to constrain all analyses to the country extent.

Table 1 Network summary statistics for Bhutan’s protected area network

Section	Metric	Value
Network Statistics	Number of Protected Areas	19
	Total Network Area (km²)	19,750.16
	Total Analyzed Pixels	256,410
	Analysis Scale (m)	300
EII Summary (PA-level means)	Simple Mean	0.6511
	Area-Weighted Mean	0.6785
	Pixel-Weighted Mean	0.6782
	Standard Deviation	0.1019
	Minimum	0.4755
	Maximum	0.8214
	Median	0.6742
	Range	0.3459
	Interquartile Range (IQR)	0.1374
	Category	Biological Corridor 1
	EII Mean	0.8214

Extreme Values (Highest/Lowest)	Area (km²)	255.55
	Category	Phibsoo Wildlife Sanctuary
	EII Mean	0.4755
	Area (km²)	287.18

EII ranges from 0 to 1, with higher values indicating greater ecosystem integrity. All calculations were derived from 300-m spatial resolution raster layers.

Ecosystem integrity index data

The Ecosystem Integrity Index (EII) dataset is publicly available and was accessed via Google Earth Engine (projects/landler-open-data/assets/eii/global/eii_global_v1). The dataset provides global terrestrial coverage at 300 m spatial resolution. The implementation and data access are documented in technical resources (Leutner, 2025), whereas the conceptual framework and global validation of the index are based on peer-reviewed literature (Sun et al., 2026). The EII integrates three complementary components:

- Functional integrity, representing ecosystem processes such as primary productivity, carbon cycling, and vegetation phenology.
- Structural integrity, describing physical habitat attributes including vegetation height, canopy cover, and landscape configuration.
- Compositional integrity, indicating the condition of species assemblages inferred from habitat-suitability modeling and patterns of species richness.

The precomputed EII layer was used directly to ensure consistency with the published methodology and globally standardized dataset. Data extraction and summary statistics were performed programmatically using a Python-based interface to Google Earth Engine. All analyses were conducted at the native 300 m spatial resolution of the EII product using the WGS84 geographic coordinate reference system (EPSG:4326).

Zonal statistics

Zonal statistics for EII and each component band were calculated for every protected area using Google Earth Engine spatial reducers (Gorelick et al., 2017). For each unit, summary metrics included the mean, standard deviation, and the 5th, 25th, 50th, 75th, and 95th percentiles. Pixel counts were retained to derive area-weighted summaries at the national-network scale. Category-level statistics were generated by aggregating protected-area-specific results according to protected-area designation (national park, wildlife sanctuary, strict nature reserve, botanical park, and biological corridor).

Counterfactual analysis

To evaluate potential effects of legal protection on ecosystem integrity, we implemented a spatial counterfactual comparison between each protected area and its surrounding landscape. For every protected area, an external buffer zone extending 10 km beyond the boundary was generated, excluding any overlapping areas of other protected areas to ensure comparison with unprotected land. Mean EII values were calculated separately for interior and buffer zones. The difference between these values ($\Delta\mathrm{EII} = \mathrm{EII}_{\mathrm{inside}} - \mathrm{EII}_{\mathrm{outside}}$) was used as an index of relative integrity, with positive values indicating higher integrity inside protected-area boundaries.

Covariate extraction

Environmental and anthropogenic covariates were extracted to characterize gradients associated with spatial variation in EII. Predictor layers included:

- Human Modification Index from the Global Human Modification dataset (CSP/HM/GlobalHumanModification; Kennedy et al., 2019).
- Tree cover (year 2000) and forest loss from Hansen Global Forest Change v1.11 (UMD/hansen/global_forest_change_2023_v1_11; Hansen et al., 2013).
- Normalized Difference Vegetation Index (NDVI) from MODIS Terra 16-day composites (MODIS/061/MOD13Q1).
- Burned-area frequency from the MODIS burned-area product (MODIS/061/MCD64A1).
- Land-cover proportions (cropland and built-up classes) from ESA WorldCover v200 (ESA/WorldCover/v200).

- Elevation from the Shuttle Radar Topography Mission (USGS/SRTMGL1_003).

For each protected area, zonal means were calculated for all covariates to generate site-level summaries.

Full covariate summaries are provided in Table S4.

Statistical modeling

Two regression frameworks were implemented to evaluate predictors of ecosystem integrity using 49,933 stratified random sample points distributed across the study area. The counterfactual model regressed EII on protected-area identity (as dummy variables), an inside–outside indicator, and elevation, with standard errors clustered at the protected-area level to account for spatial autocorrelation. The drivers model regressed EII on environmental and anthropogenic covariates, including elevation, human modification, burned-area frequency, NDVI trend, cropland proportion, and built-up proportion, also with cluster-robust standard errors. Both models were estimated using ordinary least squares. In addition, a random-forest regression was fitted to rank the relative importance of all predictor variables based on permutation-based variable importance scores (Breiman, 2001).

Validation

Empirical validation assessed whether functional-integrity patterns were consistent with independent ecosystem-condition proxies. Protected-area-level functional-integrity means were compared with NDVI temporal trend (as a proxy for vegetation greenness change) and the inverse of forest-loss proportion (as a proxy for forest condition). Pearson and Spearman rank correlations and normalized root-mean-square error (NRMSE) were calculated. All analyses were performed in Google Earth Engine and Python.

Results and Discussion

Network-level patterns

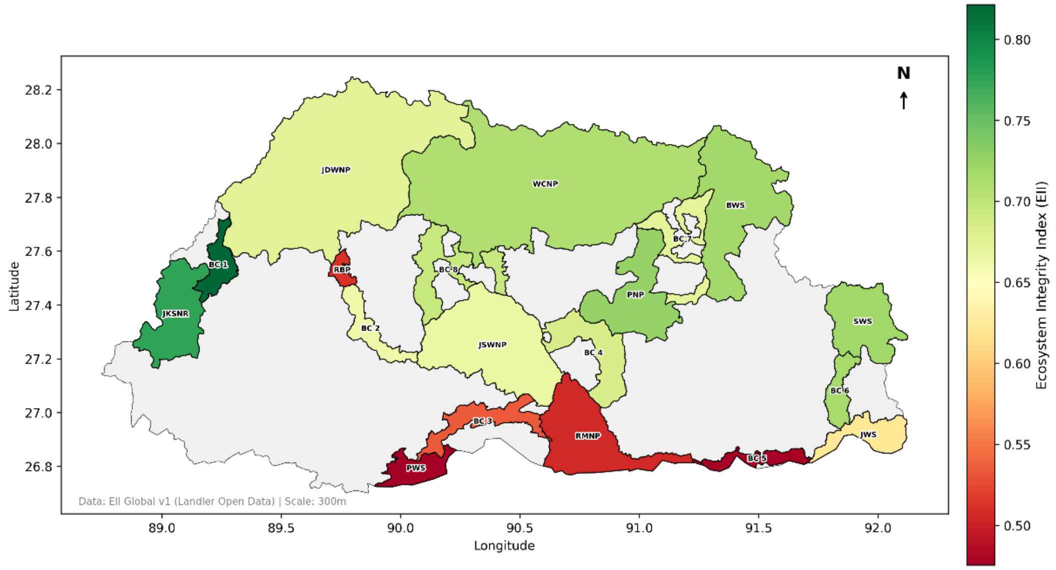
Across Bhutan’s protected-area network, 256,410 pixels at 300-m resolution were analyzed, covering 19,750.16 km^2 (Table 1). The network-wide simple mean EII was 0.6511, while the area-weighted and pixel-weighted means were 0.679 and 0.678, respectively. The standard deviation of protected-area-level means was 0.102, with values ranging from 0.4755 in Phibsoo Wildlife Sanctuary to 0.8214 in Biological Corridor 1 (Table 2; Fig. 2).

Table 2 Ecosystem Integrity Index (EII) summary statistics for Bhutan’s protected areas

Rank	**Protected area**	**Area (km^2)**	**EII mean**	**EII SD**	**EII P5**	**EII P25**	**EII P50**	**EII P75**	**EII P95**	**Pixel count**
1	Biological Corridor 1	255.55	0.82	0.09	0.64	0.77	0.84	0.89	0.94	3,450
2	Jigme Khesar Strict Nature Reserve	784.22	0.78	0.13	0.51	0.70	0.81	0.88	0.93	10,203
3	Phrumsengla National Park	906.65	0.73	0.13	0.49	0.63	0.74	0.83	0.92	11,846
4	Sakteng Wildlife Sanctuary	742.46	0.72	0.15	0.45	0.62	0.74	0.84	0.92	9,608
5	Bumdeling Wildlife Sanctuary	1,534.24	0.72	0.13	0.49	0.62	0.73	0.83	0.91	19,900
6	Biological Corridor 6	232.77	0.71	0.11	0.53	0.63	0.71	0.79	0.89	3,122
7	Wangchuck Centennial National Park	4,914.63	0.71	0.13	0.50	0.60	0.71	0.82	0.91	62,947
8	Biological Corridor 8	558.60	0.69	0.14	0.49	0.56	0.70	0.81	0.91	7,583
9	Biological Corridor 4	594.65	0.68	0.13	0.48	0.58	0.68	0.79	0.89	7,834
10	Jigme Dorji Wangchuck National Park	4,374.06	0.67	0.17	0.34	0.58	0.69	0.81	0.91	56,020
11	Biological Corridor 7	419.66	0.67	0.13	0.49	0.55	0.66	0.78	0.89	5,857
12	Jigme Singye Wangchuck National Park	1,730.06	0.67	0.13	0.47	0.55	0.67	0.77	0.89	22,168
13	Biological Corridor 2	291.76	0.66	0.13	0.47	0.56	0.66	0.77	0.88	3,916

Rank	Protected area	Area (km²)	EII mean	EII SD	EII P5	EII P25	EII P50	EII P75	EII P95	Pixel count
14	Jomotsangkha Wildlife Sanctuary	362.49	0.62	0.11	0.45	0.55	0.62	0.70	0.82	4,800
15	Biological Corridor 3	407.12	0.53	0.08	0.45	0.47	0.51	0.58	0.69	5,560
16	Royal Botanical Park	91.20	0.51	0.06	0.44	0.47	0.51	0.54	0.63	1,271
17	Royal Manas National Park	1,057.02	0.51	0.11	0.42	0.44	0.46	0.53	0.75	13,646
18	Biological Corridor 5	205.83	0.48	0.08	0.41	0.43	0.44	0.50	0.67	2,846
19	Phibsoo Wildlife Sanctuary	287.18	0.48	0.06	0.43	0.44	0.45	0.48	0.61	3,833

EII values range from 0 to 1, with higher values indicating greater ecosystem integrity. Percentiles (P5–P95) describe within-area spatial variability in EII. Pixel counts correspond to the number of 300-m raster cells used for calculations.



Data: EII Global v1 (Landler Open Data) | Scale: 300m

Fig. 2 Choropleth map of Ecosystem Integrity Index (EII) across Bhutan's protected area network. Protected areas are shaded according to mean EII value, with darker shading indicating higher integrity

Biological Corridor 1 exhibited the highest mean EII (0.8214; area = 255.55 km²), whereas Phibsoo Wildlife Sanctuary had the lowest (0.4755; area = 287.18 km²). Among national parks, Phrumsengla National Park ranked highest (mean = 0.7263), while Royal Manas National Park ranked lowest (mean = 0.5061). Fourteen of the 19 protected areas, representing 89.6% of the total network area, maintained mean EII values above 0.60, but the network-wide range of 0.3459 indicates substantial heterogeneity in ecosystem condition.

Component patterns clarify where that heterogeneity arises. Structural integrity displayed the highest network mean (0.9522) and low variability, compositional integrity was likewise high (mean = 0.9520; SD = 0.022), and functional integrity exhibited substantially greater heterogeneity (mean = 0.6547; SD = 0.1001), with values ranging from 0.4763 in Phibsoo Wildlife Sanctuary to 0.8251 in Biological Corridor 1. Variation in overall EII therefore reflects differences in ecosystem functioning more than broad differences in habitat configuration or modeled compositional condition. Full component-level statistics are provided in Table S1, and spatial component patterns are shown in Fig. S1.

Protected-area comparison

Protected areas were strongly stratified rather than tightly clustered around the network mean (Fig. 3). The strict nature reserve ranked second overall, and biological corridors spanned nearly the full network range, from 0.4781 in Biological Corridor 5 to 0.8214 in Biological Corridor 1. This spread was wider than that observed among the five national parks and indicates that connectivity units are not uniformly maintaining ecological condition.

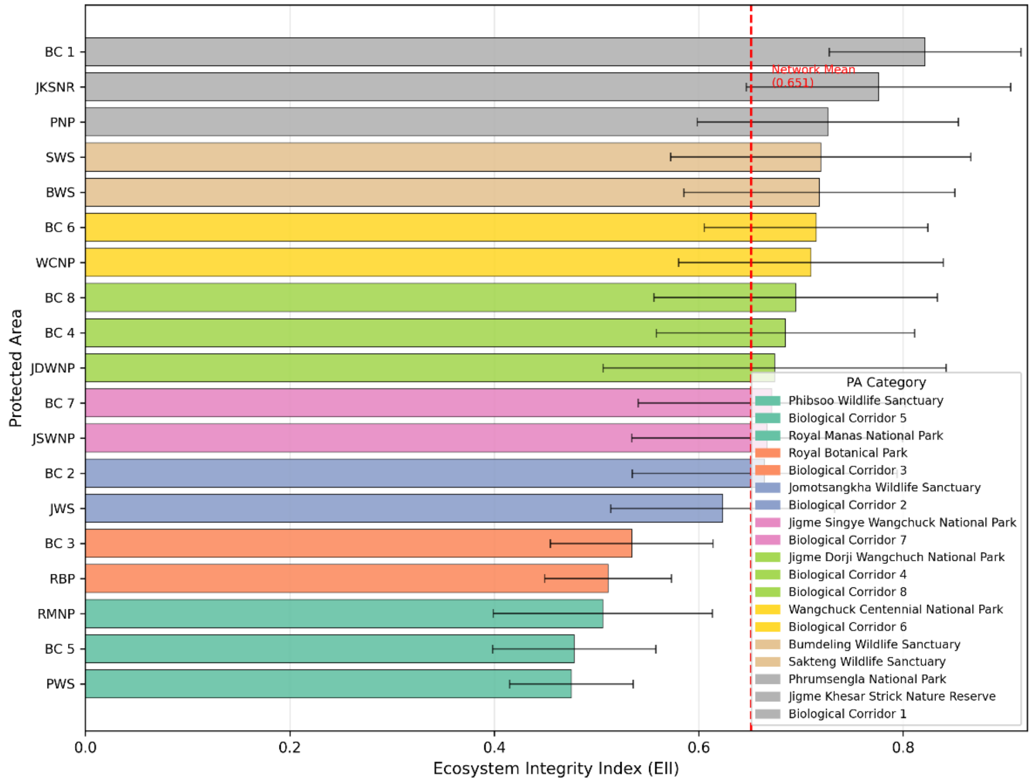


Fig. 3 Bar chart comparing mean EII values among the 19 protected areas, ranked from highest to lowest. Error bars indicate standard deviation.

The protected-area ranking also reveals a distinct low-integrity group. Phibsoo Wildlife Sanctuary, Biological Corridor 5, Royal Manas National Park, Royal Botanical Park, and Biological Corridor 3 all recorded mean EII values below 0.60, together encompassing approximately 2,048 km². Pairwise differences in mean EII ranged from 0.0027 to 0.3459, with the greatest contrast observed between Biological Corridor 1 and Phibsoo Wildlife Sanctuary. Full pairwise comparisons are provided in Table S2.

Inside–outside effects

Counterfactual comparisons showed higher integrity inside protected-area boundaries for 13 of the 19 sites, but the magnitude and direction of the effect varied sharply across the network. The largest positive ΔEII values occurred in Jigme Khesar Strict Nature Reserve (+0.0708), Sakteng Wildlife Sanctuary (+0.0701), Biological Corridor 6 (+0.0657), and Bumdeling Wildlife Sanctuary (+0.0655), pointing to stronger relative performance in several high-elevation units.

Negative contrasts were concentrated in Phibsoo Wildlife Sanctuary (−0.0562), Royal Manas National Park (−0.0376), Biological Corridor 5 (−0.0181), Royal Botanical Park (−0.0171), Biological Corridor 7 (−0.0140), and Biological Corridor 3 (−0.0117). These cases indicate that protection status did not consistently translate into higher contemporary integrity than the surrounding landscape. The counterfactual regression yielded the same network-level interpretation: the inside–outside indicator was positive but not statistically significant (coefficient = 0.0133, $p = 0.088$) once elevation and protected-area identity were included. Distributional inside–outside contrasts are shown in Fig. S2, and detailed comparisons are provided in Table S3. Protected-area-level delta EII values are summarized in Fig. 4.

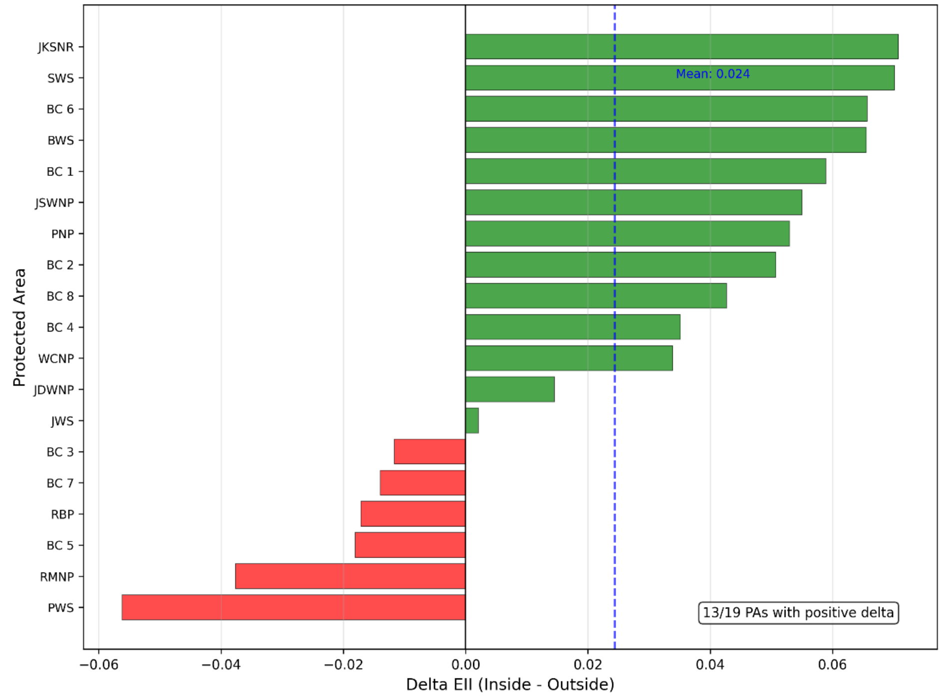


Fig. 4 Bar chart summarizing delta EII (inside minus outside) for each protected area, ordered by delta magnitude

Drivers of ecosystem integrity

Environmental gradients explained more variation in EII than legal designation alone. Elevation ranged from 453.14 m in Biological Corridor 5 to 4,314.16 m in Jigme Dorji Wangchuck National Park, and EII was positively correlated with elevation (Pearson's $r = 0.791$, $p < 0.001$). By contrast, EII declined with NDVI ($r = -0.654$, $p = 0.002$), tree cover ($r = -0.565$, $p = 0.012$), and human modification ($r = -0.536$, $p = 0.018$), reflecting the pronounced contrast between high-elevation systems and more modified lowland landscapes. Additional covariate relationships are shown in Fig. S3 and Table S4.

Regression and machine-learning results reinforced the same hierarchy of drivers. The counterfactual model explained 38.0% of the variance in EII ($R^2 = 0.380$; $n = 49{,}933$ observations across 19 protected-area clusters), and the drivers model explained 26.6% ($R^2 = 0.2661$). Elevation remained a significant positive predictor in both frameworks (counterfactual coefficient = 5.2×10^{-5}, $p < 0.001$; drivers' coefficient = 5.5×10^{-5}, $p < 0.001$), while built-up land proportion had a significant negative effect in the drivers' model (coefficient = -0.1388, $p < 0.001$). Random-forest analysis similarly ranked elevation as the dominant predictor (relative importance = 0.618, 61.8%), followed by human modification (0.207, 20.7%), mean NDVI (0.101, 10.1%), tree cover (0.039, 3.9%), and NDVI trend (0.026, 2.6%), whereas inside–outside status contributed less than 1% of total importance.

Interpretation and policy relevance

Taken together, these results indicate that Bhutan's protected-area network retains moderate-to-high overall ecological condition but does so unevenly across space and management units. The area-weighted mean EII of 0.6785 and the finding that 89.6% of total network area occurs in protected areas with mean EII above 0.60 support the view that the network broadly aligns with the ecological-condition intent of KM-GBF Target 3. However, fewer than half of the network area (47.4%, approximately 9,371 km^2) exceeded 0.70, implying that stronger ecosystem functioning is concentrated in a subset of high-integrity sites rather than distributed uniformly across the system.

This unevenness is especially important for biological corridors, which are intended to secure connectivity but span almost the full national integrity range. Biological Corridor 1 exceeded the mean EII of every core protected-area category, whereas Biological Corridor 5 ranked among the lowest sites in the country. The implication is that corridor designation alone is not a sufficient proxy for corridor quality; some corridors appear to be functioning as strong ecological linkages, while others likely require active restoration and pressure reduction if they are to support landscape connectivity effectively.

The weak and statistically non-significant associations between functional integrity and independent proxy metrics further sharpen this interpretation (Table S5; Fig. S3). NDVI trend showed a positive but non-significant relationship with functional integrity (Pearson’s $r = 0.308$, $p = 0.199$; Spearman’s $\rho = 0.312$, $p = 0.193$; $R^2 = 0.095$; NRMSE = 0.339), whereas inverse forest-loss proportion was also weakly and non-significantly correlated (Pearson’s $r = -0.212$, $p = 0.385$; Spearman’s $\rho = 0.002$, $p = 0.994$; $R^2 = 0.045$; NRMSE = 0.452). These results suggest that EII captures dimensions of ecological condition not fully represented by conventional cover-based proxies, but they also indicate that future monitoring should pair EII with field-based ecosystem metrics. From a management perspective, the immediate priority is therefore not only maintaining protected extent, but targeting monitoring and intervention toward lowland reserves and low-integrity corridors where ecosystem functioning appears most vulnerable.

Conclusion

This study provides the first spatially explicit evaluation of ecosystem integrity across Bhutan’s national protected-area network using the Ecosystem Integrity Index. Integrity values varied substantially among the 19 protected areas, ranging from 0.4755 to 0.8214, with an area-weighted network mean of 0.6785. Structural and compositional components were uniformly high across the system, whereas functional integrity exhibited greater spatial variability and closely tracked overall EII patterns.

Counterfactual comparisons indicated higher integrity inside protected-area boundaries for 13 of 19 sites, although six protected areas showed lower interior values. Elevation and human modification emerged as the dominant predictors of spatial variation, accounting for most of the explanatory power in random-forest models.

Together, these results establish a quantitative national baseline for monitoring ecosystem condition and demonstrate the applicability of standardized integrity metrics for evaluating protected-area performance in mountainous, data-limited regions. Repeated assessments through time, coupled with integration of field-based indicators, will strengthen evidence-based conservation planning in Bhutan and provide a transferable framework for other biodiverse landscapes.

Statements and declarations

Ethics approval

This study relied exclusively on secondary geospatial datasets and remotely sensed environmental indicators. No field sampling, animal handling, human participants, or social data collection were conducted; therefore, institutional ethical approval was not required. All spatial datasets were accessed through publicly available repositories or government-authorized data-sharing arrangements, and analyses complied with applicable data-use policies and licensing conditions.

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

Data availability

The Ecosystem Integrity Index dataset analyzed in this study is publicly available through Google Earth Engine at the asset path reported in the Materials and methods section. Protected-area boundary layers and derived zonal-statistics outputs used for the analysis are available from the corresponding author on reasonable request, subject to the data-sharing policies of the Royal Government of Bhutan. Analytical scripts, tables, figure outputs, and supporting metadata used to reproduce the reported results will be archived in a public GitHub repository upon publication.

Use of AI and AI-assisted technologies

AI-assisted tools were used for language editing. All scientific content, analyses, interpretations, and references were developed and verified by the authors.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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Authors' contributions

Wangdi Wangdi: Conceptualization, methodology, software, formal analysis, data curation, visualization, writing — original draft. Tashi Choden: Conceptualization, methodology, validation, interpretation, writing — review and editing, supervision. All authors read and approved the final manuscript.

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