

From Reef Condition to Seascape Governance: A Multiscale Annual-Report Assessment of Coral Triangle Resilience, 2022–2024

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Abstract

Coastal resilience assessments in the Coral Triangle frequently juxtapose protection commitments with ecological conditions without examining whether the underlying indicators refer to comparable spatial units. This study evaluates a nested annual-report dataset combining regional conservation reporting for six Coral Triangle countries with repeated coral-reef monitoring in Malaysia and site-level observations from Sabah, North Borneo. The analysis draws on the 2023 and 2024 Reef Check Malaysia survey reports and the Coral Triangle Initiative's 2024 annual report; 2022 reef-cover estimates are retained as published baselines. Percentage-point changes, site-matched contrasts, survey-coverage diagnostics, habitat-specific indicator availability and descriptive protection-stratum comparisons were calculated without pooling non-equivalent country statistics. Malaysia's reported mean live coral cover fell from 47.83% in 2022 to 45.87% in 2023 and 44.65% in 2024. In contrast, the North Borneo ecoregional mean rose from 38.13% to 39.56% between 2023 and 2024. Across 14 repeatedly reported Sabah localities, nine recorded higher cover and five lower cover; changes ranged from −10.53 to +9.95 percentage points. The 2024 regional report also documents unevenly specified marine conservation achievements across the six member countries, which cannot be interpreted as equivalent ecological outcomes. Results demonstrate that broad-scale decline can coexist with localized improvement and substantial within-region variation. A multiscale reporting framework is proposed that connects repeatable reef condition indicators with seagrass and mangrove monitoring, management effectiveness and explicitly documented subnational coverage.

Keywords : Coral Triangle; annual reports; live coral cover; North Borneo; reef resilience; marine governance.



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INTRODUCTION

The Coral Triangle spans Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste. These countries share connected marine ecosystems but differ considerably in spatial monitoring coverage, conservation institutions, and the indicators routinely reported. Regional strategies often combine expansion of marine protected areas, fisheries measures, habitat conservation, and climate adaptation. Ecological resilience, however, is observable only through condition, exposure, recovery, and functional continuity measured at appropriate scales. A country-level protection statistic cannot establish whether a particular reef has recovered, and a high local coral-cover estimate cannot demonstrate resilience across an entire seascape (Cinner et al., 2016; Darling et al., 2019; Graham et al., 2015).

The three principal coastal habitats also require different outcome measures. Coral communities respond visibly to heat exposure and reef disturbance, while seagrass distribution and condition, mangrove habitat persistence, and sedimentary carbon respond through partly distinct temporal processes. Global literature has clarified these processes but cautions against treating carbon storage, mapped habitat extent, and coral cover as interchangeable resilience proxies (Duarte et al., 2013; Howard et al., 2017; Macreadie et al., 2021; Stankovic et al., 2023). Indonesian carbon-stock evidence strengthens the scientific foundation for mangrove protection, yet it does not replace comparable site-level assessment of reefs or seagrass meadows (Murdiyarso et al., 2015; Murdiyarso et al., 2023; Analuddin et al., 2024).

Annual reports provide a distinct empirical opportunity because they preserve spatially identified operational results, recurrent observation years, monitoring coverage, and management activities. Reef Check Malaysia reports publish standardized substrate assessments by ecoregion and by named reefs

in Sabah. The Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security (CTI-CFF) separately reports national and regional conservation activities across its six member countries. The reports contain different classes of evidence: ecological measurements, survey effort, and implementation or governance descriptions. Those classes can be compared within their own units but should not be amalgamated into a synthetic biodiversity score.

The scientific problem addressed here is the divergence between regional conservation reporting and local ecological change. In 2024, the Coral Triangle region experienced continuing climate-related pressures while local programs recorded different reef-cover trajectories, even within a single ecoregion. Repeatedly surveyed localities make those spatial contrasts measurable; regional annual reports show the institutional setting in which such results are interpreted. Earlier reef studies connect thermal stress to bleaching and loss (Hoegh-Guldberg et al., 2007; Hughes et al., 2017; Hughes et al., 2018; Sully et al., 2019; Donovan et al., 2021; Dixon et al., 2022), but the present research does not use journal articles as quantitative observations.

This study therefore pursues three objectives: to describe changes in live coral cover from annual monitoring summaries at national and ecoregional levels; to quantify variation across 14 repeatedly reported Sabah localities during 2023–2024; and to place those results within the six-country governance information documented by the CTI-CFF annual report. Its contribution is a traceable, spatially nested assessment based on annual-report indicators rather than bibliographic counts, with a practical framework for coordinating reef, mangrove, seagrass, and management reporting.

RESEARCH METHOD

A retrospective secondary-data design was applied to publicly released annual monitoring and institutional reports. Ecological observations were extracted from Reef Check Malaysia, Status of Coral Reefs in Malaysia, 2023 (published 2024) and Status of Coral Reefs in Malaysia, 2024 (published 2025). The national 2022 reference value was retained from the 2023 report to establish a three-year descriptive baseline. Regional governance information was drawn from the CTI-CFF Annual Report 2024 (released in 2026), which covers the six participating Coral Triangle countries. Annual reports, rather than DOI-indexed scholarly papers, were the empirical units of extraction; the scholarly literature was reserved for defining ecological mechanisms and interpreting the observations.

The analysis followed three nested geographical levels. Level 1 covered the six-country CTI-CFF institutional context but did not estimate country-specific reef condition from management announcements. Level 2 examined the Malaysia ecoregions of Sunda Shelf, Malacca Strait, and North Borneo using annually reported mean live coral cover (LCC) and site counts. Level 3 consisted of 14 named Sabah localities that had a directly comparable LCC entry in both the 2023 and 2024 reports: Kapalai, Lahad Datu, Lankayan, Laraman, Mabul, Mantanani, Matakong, Pulau Penyu, Pulau Tiga, Sipadan, Tunku Abdul Rahman Park (TARP), Tun Mustapha Park (TMP), Tun Sakaran Marine Park (TSMP), and Usukan Cove. Labuan occurred in the 2023 locality table but not in the comparable 2024 table and was therefore excluded from the matched locality analysis.

For each locality, extraction preserved the reported geographic label, mean LCC (%), number of surveyed sites in each year, and 2024 protection descriptor. Point changes were calculated as $\Delta LCC = LCC(2024) - LCC(2023)$, expressed in percentage points (pp), not percent change. Reported national and ecoregional values were compared directly; locality means were not averaged to reconstruct ecoregional or national means because locality-level sampling weights and coverage can differ. Median, mean, minimum, maximum, direction of change, and protection-stratum descriptive contrasts were computed across the 14 matched localities. Statistical hypothesis testing and causal attribution were not attempted because the available observations are aggregated, survey effort varies at some localities, and the design has only two matched years.

Annual reporting uses Reef Check's standardized point-intercept substrate classification; LCC combines live hard and soft coral. Reef condition classes were retained in their published form: poor below 25%, fair from 25% to below 50%, good from 50% to below 75%, and excellent at least 75%. These are descriptive habitat-condition categories, not validated temporal resilience thresholds. The CTI-CFF country accounts were examined for explicitly reported conservation instruments, management initiatives, training, and location-specific implementation examples. Missing ecological metrics were classified as not reported in the selected annual-report material rather than coded as ecological absence.

Table 1. Annual-Report Sources, Analytical Scale, and Permitted Comparisons

Source / reporting year	Spatial unit	Extracted field	Analytical use
Reef Check Malaysia (2024), survey year 2023	Malaysia; three ecoregions; Sabah areas	Sites, LCC, protection descriptors	2023 baseline and 14-area matches
Reef Check Malaysia (2025), survey year 2024	Malaysia; three ecoregions; Sabah areas	Sites, LCC, substrate/impact context	2024 comparison, change calculations
2022 baseline as reproduced in 2023 report	Malaysia national mean	LCC = 47.83%	Descriptive 2022–2024 national trajectory
CTI-CFF (2026), activity year 2024	Six CTI-CFF countries	Conservation actions and reported outputs	Governance context; not ecological pooling

Reproducibility was prioritized through direct numeric transcription and explicit identification of the source-report tables. Values are retained at the published precision of two decimal places. Site means and country achievements are not scaled to total reef area, no unsurveyed habitat values are imputed, and differences between sampling periods are described as reported changes rather than site-specific causal treatment effects. Figures were generated from the tabulated source values, while the original annual-report classifications are preserved.

RESULTS AND DISCUSSION

Temporal reef trends and unequal ecoregional change

The monitored national mean LCC declined from 47.83% in 2022 to 45.87% in 2023 and 44.65% in 2024. These represent successive declines of 1.96 pp and 1.22 pp, with a cumulative decrease of 3.18 pp across two intervals. The figures describe the reported surveyed reefs and are not estimates of a probability-based trend for every reef across Malaysia. Survey coverage was 323 sites in 2022, 326 in 2023, and 315 in 2024; the varying site totals reinforce the need to separate repeated observation from changes in the composition of the sampling network (Reef Check Malaysia, 2024, 2025).

Table 2. National Annual Monitoring Observations And Changes In Live Coral Cover

Survey year	Surveyed sites	Mean LCC (%)	Change from prior year (pp)
2022	323	47.83	—
2023	326	45.87	–1.96
2024	315	44.65	–1.22

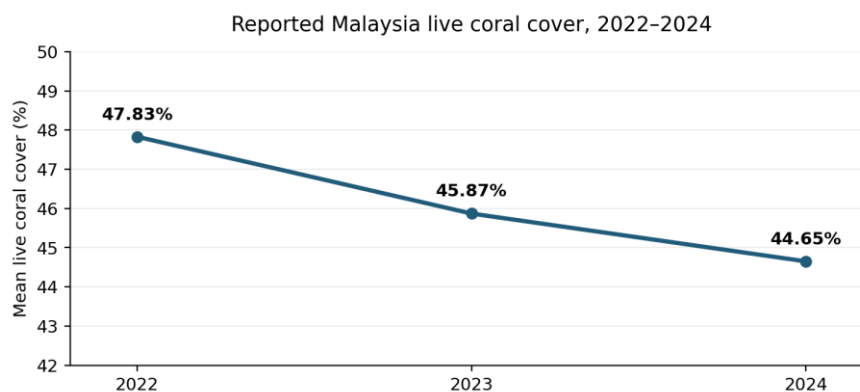


Figure 1. Malaysia Reported Live Coral Cover, 2022–2024 (Reef Check Malaysia, 2024, 2025).

National aggregation conceals contrasting ecoregional trajectories. In the Sunda Shelf, mean reported LCC declined from 53.27% in 2023 to 50.21% in 2024 (−3.06 pp); in the Malacca Strait, it declined from 41.90% to 36.36% (−5.54 pp). North Borneo, by contrast, increased from 38.13% to 39.56% (+1.43 pp). Site counts simultaneously changed from 161 to 157 in Sunda Shelf, 23 to 22 in Malacca Strait, and 142 to 136 in North Borneo. Although North Borneo remains lower in mean coral cover than Sunda Shelf, its direction of reported change differs from the other ecoregions. This illustrates why regional adaptation decisions require disaggregated monitoring rather than exclusive reliance on countrywide averages.

Table 3. Ecoregional Reported Cover and Monitoring Coverage, 2023–2024

Ecoregion	Sites 2023	Sites 2024	LCC 2023 (%)	LCC 2024 (%)	Δ pp
Sunda Shelf	161	157	53.27	50.21	−3.06
Malacca Strait	23	22	41.90	36.36	−5.54
North Borneo	142	136	38.13	39.56	+1.43

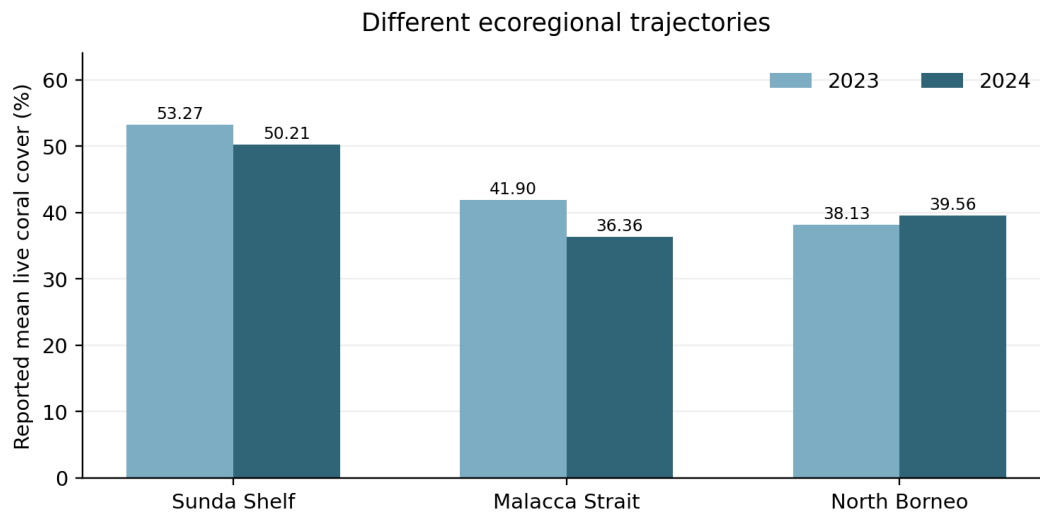


Figure 2. Distinct ecoregional reef-cover trajectories from the 2023 and 2024 annual surveys.

The divergence is consistent with reef systems responding to locally heterogeneous combinations of ocean warming, extraction, tourism, sediment exposure, and recovery opportunity. It does not establish why one ecoregion improved while another declined. Reefs are subject to nonlinear disturbance and recovery processes, as documented in longer-term comparative studies (Graham et al., 2015; Darling et al., 2019; Donovan et al., 2021). The annual reports additionally record that bleaching was observed in nearly 90% of the islands or areas surveyed in 2024 and identify physical impacts from lost nets, trash, anchor damage, and destructive fishing. Those indicators describe substantial pressure but do not provide a matched causal model of local LCC change.

Site-matched contrasts across North Borneo

Fourteen named Sabah localities occur in both annual surveys and form the most spatially informative comparative component. Their 2024 reported mean LCC ranged from 13.98% at Tunku Abdul Rahman Park to 63.28% at Sipadan, a cross-locality spread of 49.30 pp. Nine localities showed increased cover and five decreased. The unweighted mean locality change was +0.76 pp and the median change +2.01 pp. Neither value is the North Borneo ecoregional mean change because locality survey counts are unequal and the matched set does not exactly reproduce the full ecoregional sampling frame.

Table 4. Paired Live Coral Cover By Sabah Locality; All Changes In Percentage Points

Locality	n 2023	n 2024	LCC 2023	LCC 2024	Δ pp
Kapalai	6	5	21.15	20.50	-0.65
Lahad Datu	17	18	35.26	35.69	+0.43
Lankayan	15	12	47.58	49.53	+1.95
Larapan	5	5	56.38	58.50	+2.12
Mabul	6	6	23.02	22.29	-0.73
Mantanani	12	12	30.94	33.00	+2.06
Mataking	6	6	36.56	26.88	-9.68
Pulau Penyu	9	9	32.42	39.31	+6.89
Pulau Tiga	7	7	33.39	22.86	-10.53
Sipadan	12	12	56.88	63.28	+6.40
TARP	8	8	21.09	13.98	-7.11
TMP	18	18	42.19	44.83	+2.64
TSMP	12	12	45.83	55.78	+9.95
Usukan Cove	6	6	25.73	32.67	+6.94

The largest positive changes were recorded at TSMP (+9.95 pp), Usukan Cove (+6.94 pp), Pulau Penyu (+6.89 pp), and Sipadan (+6.40 pp). In contrast, Pulau Tiga (−10.53 pp), Mataking (−9.68 pp), and TARP (−7.11 pp) showed the most pronounced decreases. At Mataking and Pulau Tiga, the surveyed-site counts were unchanged between the report years, reducing one particular coverage concern but not ruling out shifts in transect location, condition, disturbance, or observer variation. Increases at named localities similarly do not prove that the 2024 marine heatwave had no effect.

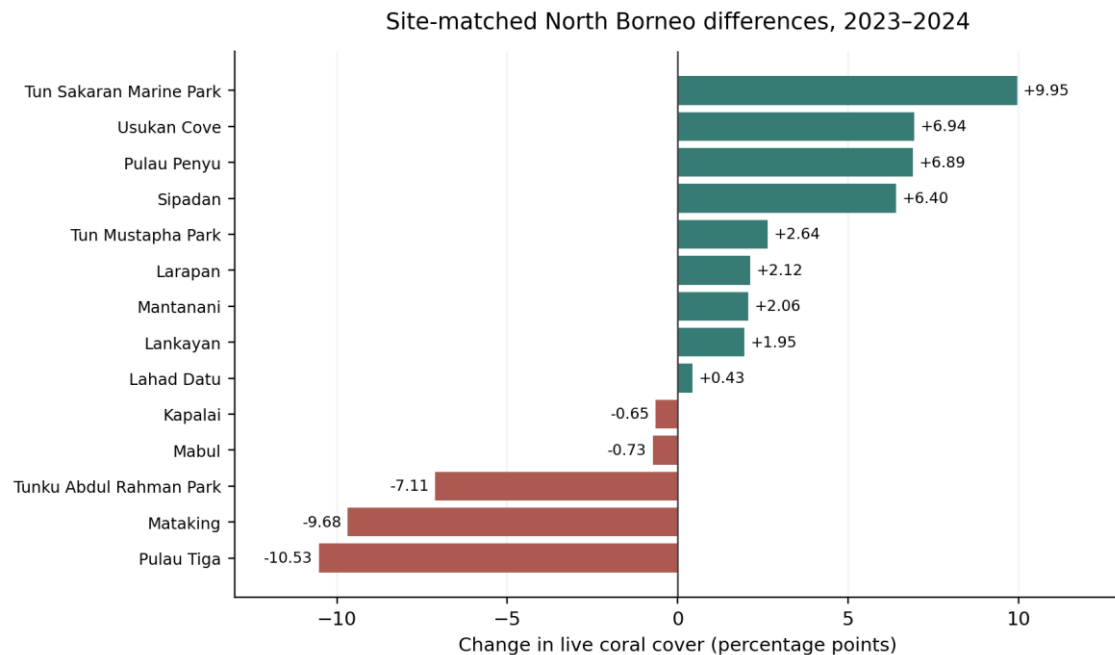


Figure 3. Changes In Reported Live Coral Cover Across 14 Localities Repeatedly Listed In Sabah Annual Surveys.

The two reports provide corresponding local means, not matched transect-level observations or measures of uncertainty. The observed differences should therefore be regarded as surveillance signals suitable for targeted field investigation. A paired two-year change at a reported locality is not equivalent to a repeated-measures experiment, especially where the number of sites changes: for example, Lankayan declined from 15 surveyed sites in 2023 to 12 in 2024, and Lahad Datu increased from 17 to 18. This limitation constrains ecological attribution while retaining the practical value of detecting where management review is most urgent.

Reef condition, protected areas, and local management signals

Classification of the 2024 locality-level means yielded three localities with good coral cover (Larapan, Sipadan, and TSMP), seven with fair cover, and four with poor cover (Kapalai, Mabul, Pulau Tiga, and TARP). No locality mean reached the excellent category. This heterogeneous profile is especially visible within the named marine-park system: Sipadan and TSMP were above 50% LCC, whereas TARP and Pulau Tiga were below 25%. A protected designation alone does not eliminate differences in exposure, fishing enforcement, historical damage, or reef recovery (Cinner et al., 2016; Darling et al., 2019).

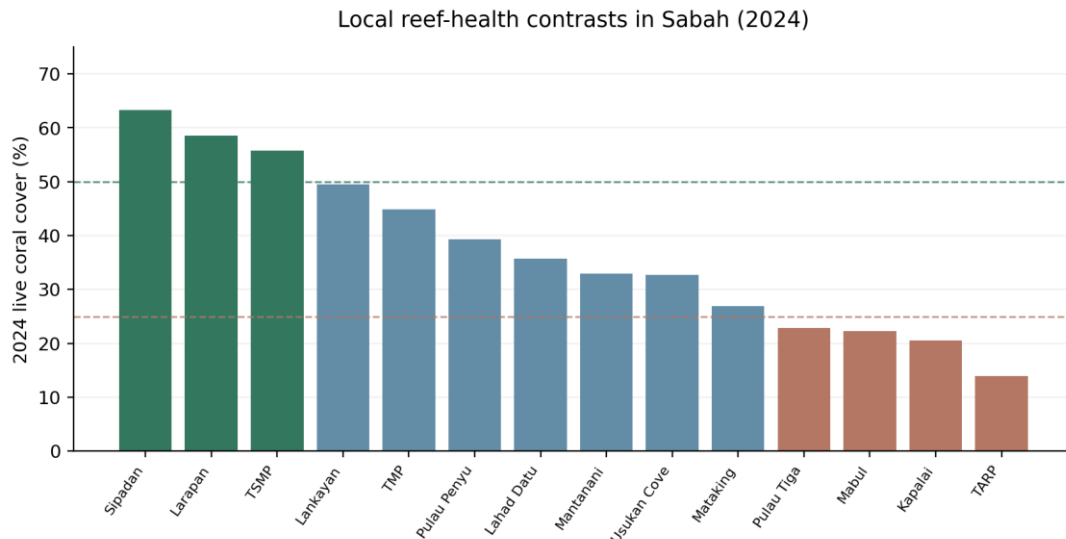


Figure 4. Sabah Locality Condition Gradient In 2024; Dashed Lines Indicate The 25% And 50% Category Boundaries.

Table 5. Descriptive Locality-Level Differences By 2024 Reported Protection Designation

Designation	Localities	Mean Δ pp	Median Δ pp	Increase	Decrease
Protected / managed area	7	+1.46	+2.64	5	2
Unprotected in source table	7	+0.07	+0.43	4	3
All paired localities	14	+0.76	+2.01	9	5

This descriptive grouping yields a mean change of +1.46 pp across seven protected or managed localities compared with +0.07 pp across seven entries listed as unprotected. The comparison is not a measure of management effectiveness: designations are not randomized, localities differ in ecological histories, monitoring intensity, and exposure, and some protected areas reported major declines. The annual report notes dynamite-fishing damage on 64% of the Sabah reefs surveyed in 2024, a statistic referring to surveyed reefs and not to the 14 locality-level change values. Regional reporting of enforcement, tourism, gear damage, and reef mortality alongside annual coral cover is necessary before a defensible impact evaluation could be attempted.

Six-country conservation context and the limits of indicator transfer

The CTI-CFF Annual Report 2024 provides the broader governance layer covering Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste. Its country accounts highlight various forms of marine-area protection, fisheries governance, participatory management, regional coordination, and technical capacity building. These narrative and administrative achievements are relevant to implementation, but they have different denominators and were not recorded using a

shared ecological sampling frame. The results cannot be converted into a comparable six-country score of reef resilience or total multi-habitat recovery.

Table 6. Multicountry Annual-Report Evidence And Appropriate Interpretive Boundary

CTI-CFF country	2024 report evidence / example	Interpretive category
Indonesia	29.3 million ha of MPAs reported; 382 identified OECMs covering 10.2 million ha	Conservation coverage; not reef recovery
Malaysia	Coral reef survey and ecosystem governance; detailed North Borneo localities in RCM reports	Ecological monitoring + management
Papua New Guinea	MPA initiatives described in the Bismarck Sea and Manus Province	Subnational co-management activity
Philippines	Siete Pecados Marine Park Blue Park Award; ASEAN ENMAPS network-management initiative	Management quality and connectivity
Solomon Islands	National Plan of Action for Marine Turtles 2023–2027 launched in July 2024; community conservation	Species protection and community stewardship
Timor-Leste	11 fisheries officers trained in eDNA sampling at Atauro Island	Local monitoring capacity; not habitat trend

Indonesia’s reported protected-area extent and Timor-Leste’s eleven trained fisheries officers are numerically concrete but measure completely different things. Similarly, the Philippines’ conservation recognition and Papua New Guinea’s subnational protected-area activities demonstrate distinct governance processes, not directly observed changes in live coral cover. At the monitoring end, the Sabah series is unusually detailed by locality but restricted to the Malaysian portion of the Coral Triangle. The annual reports consequently support a cross-country assessment of reporting architecture and documented action, not a statistically harmonized ecological ranking among the six states.

This mismatch also extends to coastal habitat types. Mangroves provide carbon storage, shoreline and habitat functions whose assessment requires compatible mapped extent, forest structure, hydrology, and stock or flux measures (Adame et al., 2021; Friess et al., 2019; Goldberg et al., 2020; Bunting et al., 2022; Richards & Friess, 2016; Sasmito et al., 2019; Sidik et al., 2018; Rahman et al., 2024; Roy et al., 2024). Seagrass requires repeated spatial extent, species composition, meadow condition, and functional indicators; published syntheses document ongoing challenges of coverage and comparability (Fortes et al., 2018; McKenzie et al., 2020; Unsworth et al., 2019). None of those distinct ecological outcomes can be inferred from coral-cover means or designation areas.

A reporting architecture for integrated seascape resilience

An operational architecture should preserve the observed hierarchy rather than merge all indicators into an additive index. The first layer documents country-level measures, relevant laws and conservation instruments, funding, and management capacity. The second layer records ecoregional coverage and standardized ecological condition indicators. The third layer links repeated local observations to management actions and stressor exposure. Cross-habitat modules are then attached at the same spatial units for mangroves and seagrass; their indicators need not be identical to reef indicators, but their observation dates, geographic footprints, units, and uncertainty conventions should

be documented consistently. This structure avoids mistaking the number of monitoring sites, hectares designated, and habitat health for interchangeable evidence.

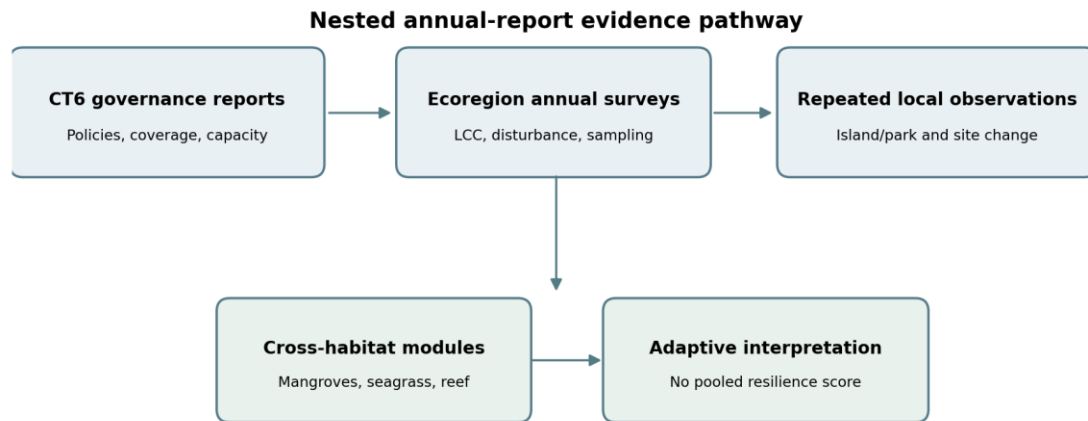


Figure 5. Proposed Nested Pathway Connecting Annual Regional Governance Records With Local Ecological Monitoring.

Table 7. Minimum Interoperable Reporting Fields For A Coral Triangle Annual-Monitoring Platform

Domain	Required report field	Suitable interpretation
Reef condition	Survey year, site ID, LCC, benthic impacts, sampling design	Within-site or within-ecoregion change
Seagrass condition	Meadow polygon, cover/density, species, observation date	Condition and persistence of mapped meadows
Mangrove condition	Forest extent, canopy/structure, disturbance and carbon method	Habitat function and stock continuity
Governance	Protected area and OECM IDs, enforcement / capacity measures	Management effort and institutional performance
Spatial matching	Site coordinates, ecoregion, country, and observation interval	Traceable cross-habitat linkage
Uncertainty	n, detection method, missingness, error or interval where available	Comparability and limitations

The immediate value of this approach is illustrated by the Sabah results: a national mean decline did not imply declining coral cover in every ecoregion, and an improving North Borneo mean did not imply increasing cover at all named localities. Annual-report-derived local measurements pinpoint possible management priorities at Matakong, Pulau Tiga, and TARP while identifying contrasting improvement at TSMP, Usukan Cove, and Sipadan. These are hypotheses for follow-up monitoring and site management, not evidence that a given intervention caused ecological recovery. Larger longitudinal analyses should use identical or transparently crosswalked transects, explicit heat-exposure measures, protected-area enforcement records, and appropriately adjusted site-level uncertainty.

These requirements also bear on socioeconomic and ecological function. Reefs sustain fisheries and coastal benefits that can decline even when limited components of cover recover (Eddy et al., 2021). Regionally differentiated climate hazards and management pressures mean that identifying local ecological trajectories is a prerequisite for responsible use of regional conservation achievements. Annual reports can constitute a powerful data source when their indicators are standardized and spatially

linked; otherwise, the credibility of integration depends on resisting false equivalence among hectares, coral percentages, carbon quantities, training events, and biodiversity outcomes.

CONCLUSION

Annual-report data reveal multiscale divergence in coastal resilience monitoring across the Coral Triangle. Malaysia's reported live coral cover decreased by 3.18 percentage points from 2022 to 2024, but its North Borneo ecoregional mean increased by 1.43 percentage points during 2023–2024. Across 14 named Sabah localities reported in both years, nine improved and five declined, with changes ranging from –10.53 to +9.95 percentage points. These site-level differences show why broad averages and marine protection designations are insufficient substitutes for local ecological trajectories. The CTI-CFF annual report demonstrates extensive conservation activity across six countries, although its country achievements are not measured with a single comparable ecological denominator. An integrated annual-report system should link country governance measures to repeated reef, seagrass, and mangrove observations at identified subnational units, retain observation effort and uncertainty information, and distinguish ecological outcomes from management inputs. Direct monitoring at common geographic and temporal resolutions is the principal requirement for evaluating functional resilience rather than merely documenting regional commitment.

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