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Linking blue finance with ecological condition and coastal tourism under marine warming in Indonesia

Yingzheng Liu

liuyingzheng@stud.assist.ac.kr

aSSIST University

Fei Huang

aSSIST University

Article

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Abstract

Blue finance aims to sustain coastal ecosystems and tourism, but evaluating its benefits requires compatible financial and environmental records. We examine Indonesian evidence for 2015–2025 using financial reconciliation, ecological comparisons, revenue accounting and retrospective tourism prediction. Six conservation grant packages report cumulative expenditure of 41.10 billion Indonesian rupiah through 2022. Restoration-specific costs and intervention boundaries remain unresolved. At SD Point, raw hard-coral cover is 21.12 percentage points higher at the restoration locality than at the rubble locality, without independent site replication or a verified funding link. Gili Matra person-ticket receipts increased by 66.04% between 2023 and 2024, but tariff and collection changes prevent interpreting this as visitor growth. A completion-report economic model estimates positive returns across twelve protected areas using assumed counterfactual benefits; these differ from measured project effects. Across 24 evaluation months, a seasonal Bali visitor baseline outperforms ridge prediction with or without regional thermal indicators. The evidence supports expenditure accounting, ecological contrasts and revenue trends, while additional ecological benefits, net tourism income and ecological mediation remain unidentified.

Introduction

Coastal adaptation requires evidence that financed interventions sustain ecosystem services under climatic disturbance. In tourism destinations, expenditure must connect to ecological changes and to services that visitors use. Each link requires its own measurement; finance, habitat condition and tourism growth cannot serve as interchangeable indicators of resilience.

Marine thermal extremes can disrupt ecological communities and the services they provide [1]. Recurrent coral bleaching demonstrates the scale of the challenge [2], but ecological responses are not spatially uniform. A recent analysis in Nature Communications examined how marine protection relates to reef fish community stability under warming [3]. Research from Hawai‘i further shows that reducing local pressures on land and at sea can support coral reef persistence after heat stress [4]. These studies motivate an explicit test of local buffering. They do not establish that any protected area, financing instrument or destination will maintain the same function under every level of thermal exposure.

The relationship between conservation finance and tourism depends on two distinct links. Expenditure must first correspond to an intervention and a measurable ecological response. That response must then affect the activities captured by the tourism outcome. A reef-dependent business might benefit while provincial visitation remains unchanged, because provincial totals also include cultural, urban and visiting-friends-and-relatives travel. Conversely, transport access and domestic demand can support tourism recovery while ecological condition declines. Spatial valuation of reef-related tourism illustrates why on-reef and reef-adjacent activities need to be distinguished from broad destination totals [5].

Blue finance provides a policy setting in which to examine these boundaries, but the financial label cannot identify treatment. Early blue bond scholarship highlights gaps between reported conservation outputs and demonstrated outcomes [6]. A financing instrument may support new activity, refinance expenditure already incurred or pay for infrastructure whose tourism effects operate through access and protection rather than habitat recovery. Its nominal value also depends on currency, accounting stage and the year in which funds are recorded. A credible test must follow project implementation and outcomes instead of assigning a national issuance amount to every coastal province.

Indonesia links coastal livelihoods, environmental assets and development policy [7]. Its Ministry of Finance reports sovereign blue bond issuances of 20.7 billion Japanese yen (JPY) in 2023 [8] and JPY25 billion in 2024 [9]. The 2015–2025 window spans these milestones and varied thermal conditions, but issuance does not establish provincial treatment. Project implementation and geographically matched outcomes determine admissible comparisons.

We ask which components of the blue finance–ecology–tourism relationship can be measured consistently with existing public records. The completed analyses examine destination-attributable expenditure, comparability of ecological observations and tourism outcomes, and whether regional thermal indicators improve a simple tourism prediction

benchmark. Financial effects and ecological mediation require treatment and outcome correspondence beyond a shared destination name. The present study therefore evaluates measurement and predictive evidence without estimating a project treatment effect.

We integrate six local grant packages, ecological sources for three marine protected areas (MPAs) and tourism measurements at provincial and destination scales. We preserve each observation's geographical support, accounting stage and measurement definition. Source disagreements and failed joins are reported alongside completed descriptive and predictive results. This approach retains the policy question of coastal resilience while distinguishing the relationships supported by the data from those that remain unidentified.

Results

Complete regional thermal observations

The retrieved National Oceanic and Atmospheric Administration (NOAA) East Java and Bali archive contains 4,018 unique daily dates between 1 January 2015 and 31 December 2025. All expected dates are present. Aggregation yields 132 complete months and four monthly indicators: mean representative sea surface temperature (SST), mean representative temperature anomaly, maximum degree heating weeks (DHW) and days with HotSpot at least 1°C. The 528 indicator values are measurements of related properties across 132 regional months, not 528 independent samples. Source hashes and an offline reconstruction are provided with the data package [10, 11].

Repeated peaks differ across thermal indicators

The annual maximum DHW was 17.9871°C-weeks in 2016, 15.7043°C-weeks in 2020 and 15.9357°C-weeks in 2024. These are the three largest annual maxima in the recovered 2015–2025 regional record. Their corresponding annual counts of days with HotSpot at least 1°C were 160, 116 and 146. The annual maximum DHW in 2025 was 7.1914°C-weeks, with 45 threshold-exceedance days. Supplementary Table S1 reports every study year, avoiding selection of only the largest episodes.

These archive summaries describe regional thermal exposure, not bleaching mortality or independently identified marine heatwave events under a duration-and-climatology definition [12]. Spatial-representation uncertainty remains; no inferential tests are attached to annual maxima.

Verified tourism coverage and contrasting aggregate trajectories

The Statistics Indonesia (BPS) Bali table supplies all 132 monthly domestic visitor counts for 2015–2025; each annual sum matches its published total. No month is missing, duplicated or imputed. The original provider is the Bali Government Tourism Office survey [13]. Calendar matching yields 132 paired tourism–NOAA months, while retaining their different geographical coverage. Figure 1 shows the paired series.

Annual domestic visits increased from 7,147,100 in 2015 to 10,545,039 in 2019, then fell to 4,596,157 in 2020 and 4,301,592 in 2021. The 2020 decline was 56.41% relative to 2019. By 2024 the count reached 10,120,786, or 95.98% of the 2019 total, before declining 5.02% to 9,612,511 in 2025. These percentages are recomputed from the verified counts. Supplementary Table S1 and Fig. 1 report the observed coverage and trajectory, without labeling visit recovery as ecological recovery.

The coexistence of higher visitation and thermal stress in 2024, followed by lower visits and DHW in 2025, is descriptive. Different spatial coverage and other tourism drivers prevent attributing these trajectories to temperature.

A seasonal baseline outperformed two ridge benchmarks

All three models use the same 24 evaluation months in January 2024–December 2025. Penalty selection uses 48 earlier development origins in 2020–2023; both ridge models select 10. Coefficients and scaling are refitted using earlier targets at each origin. Unverified historical release dates mean this comparison assumes previous-month availability of revised historical records.

Seasonal naive prediction, which uses the count from the same month of the previous year, achieved a pooled mean absolute error (MAE) of 80,393.83 visits. The history-only ridge model achieved 113,705.20, and the otherwise matched model adding previous-month sea surface temperature anomaly (SSTA) and DHW achieved 115,431.80. Corresponding root mean squared error (RMSE) values were 105,318.53, 178,160.79 and 179,752.97; seasonal mean absolute scaled error (MASE) values were 0.424, 0.593 and 0.604 [14]. Figure 2 visualizes the retained predictions and errors. Table 1 reports each year as well as pooled results. Adding thermal indicators reduced the ridge model's MAE slightly in 2024 but increased it in 2025, producing a pooled MAE 1.52% higher than the history-only ridge model. Neither ridge variant outperformed seasonal naive prediction in either evaluation year.

All years and models are retained. Twenty-four serially ordered errors limit broader performance inference; no significance test or universal ranking is asserted. Weak incremental prediction does not establish the absence of an environmental effect, and no project-effect model was estimated.

Table 1
Retrospective prediction comparison

Period	Model	n	MAE visits	RMSE visits	MASE
2024	Seasonal naive	12	92,396.58	120,850.33	0.475
2024	History ridge	12	130,316.56	190,568.18	0.661
2024	History plus thermal	12	127,999.89	194,683.40	0.651
2025	Seasonal naive	12	68,391.08	87,058.51	0.374
2025	History ridge	12	97,093.84	164,822.03	0.525
2025	History plus thermal	12	102,863.71	163,464.47	0.557
2024–2025	Seasonal naive	24	80,393.83	105,318.53	0.424
2024–2025	History ridge	24	113,705.20	178,160.79	0.593
2024–2025	History plus thermal	24	115,431.80	179,752.97	0.604

n denotes the number of common evaluation months. Penalty selection uses 2020–2023 only; evaluation covers common 2024–2025 origins. Scaling and coefficients use earlier observations. Both ridge penalties equal 10. Errors are retrospective, without verified historical release dates. MASE uses the seasonal training-history scale at each origin. No claim of statistical superiority or causal interpretation.

Project-level finance and ecological observations

Official Indonesia Climate Change Trust Fund (ICCTF) reports identify seven packages under the Coral Reef Rehabilitation and Management Program—Coral Triangle Initiative (COREMAP-CTI) grant, six assigned to Nusa Penida, Gili Matra and Gili Balu, and one shared assessment covering Bali, West Nusa Tenggara and East Nusa Tenggara [15, 16]. We recover 19 dated payments in 2021 and seven annual disbursement amounts for 2022. For every package, the sum of the 2021 payments and 2022 annual disbursement exactly reproduces the reported cumulative expenditure in Indonesian rupiah (IDR) at the

end of 2022. Contract commitments, annual flows and cumulative totals are stored separately and never added together. These are project-reported expenditure records, not independently verified bank transactions.

The six local packages report cumulative expenditure of IDR41,096,384,252: IDR12,044,886,162 for Nusa Penida, IDR17,492,262,734 for Gili Matra and IDR11,559,235,356 for Gili Balu (Table 2). The additional IDR9,787,830,577 shared assessment package is not allocated among destinations. The packages combine management, infrastructure, ecosystem planning and livelihoods; none of these totals is a coral-restoration-only cost. They represent conservation grant finance, not a traced allocation from Indonesia's 2023 or 2024 blue bonds. The national issuance amounts remain contextual evidence [8, 9].

Table 2
Destination attributable grant expenditure

Destination	2021 payments IDR billion	2022 expenditure IDR billion	Cumulative IDR billion
Nusa Penida	4.516	7.529	12.045
Gili Matra	3.684	13.808	17.492
Gili Balu	4.016	7.543	11.559

Nominal IDR. Rounding is for display only; the workbook preserves integers. Six local packages; GP7 shared assessment is excluded. The 2021 dated payments plus 2022 annual disbursements reconcile to the Q4 2022 cumulative expenditure for all seven packages. Package expenditure includes multiple activities and is not coral-restoration-only spending [15, 16].

Contracts for the six local packages were signed in January–April 2021, with amended endpoints in November–December 2022. GP5 reef rehabilitation occurred in October–December 2022 [16]; contract, payment and ecological treatment dates therefore differ. The 2023 social monitoring report identifies Nusa Penida rehabilitation in Ped village and subsequent asset transfer [17]. An implementing partner describes reef stars in Ped, fish domes in Suana and concrete structures in Lembongan in early August 2022 [18]. The archive date and retrospective account do not establish an exact deployment day. These records provide village-level timing, without verified treatment polygons or dive coordinates.

The completion report publishes live coral cover for each of the three MPAs in 2021 and 2022 [19]. Nusa Penida changes from 42.71% to 34.00%, Gili Matra from 21.69% to 38.40%, and Gili Balu from 34.72% to 26.90% (Supplementary Table S3; Supplementary Fig. S2). The respective changes are − 8.71, + 16.71 and − 7.82 percentage points. These six aggregates can be linked to project packages by MPA and year, but the table does not provide exact survey dates, station coordinates, depth, denominators or sampling uncertainty. Neither year is established as a comparable preintervention baseline. The different directions cannot be attributed to expenditure or thermal exposure.

A closer project–outcome link is available for GP5. The Q4 2022 report describes monitoring one month after transplantation and mentions November to mid-December 2022 without an unambiguous observation date. It reports survival of up to 93% at Gili Air, around 98% at Gili Meno and 95% at Gili Trawangan, with 95% overall [16, p. 30]. The overall rate overlaps the island rates and is not a fourth independent sample. Missing fragment denominators, exact observation dates and comparison plots preclude precision estimates or financial-effect claims. Short-term fragment survival is not reef-wide cover or durable resilience under warming.

The inherited CoralNet source 3606 archive contains 147 visits at 12 Nusa Penida sites during 2022–2025 and 55,125 annotated points [20]. Proportions retain all point labels in the denominator. Visit coordinates, protocol identity and concurrent underwater temperature links remain unverified. The shared Ped name does not place CoralNet transects within GP4 activity footprints. No visit is assigned verified project exposure or substitute sea-grid temperature.

Geolocated surveys and protocol comparability

A published January 2022 survey supplies ten Gili Balu station coordinates and hard-coral cover estimates, with a stated depth range of 7–8 m, three 50 m point-intercept transects per station and 5 m gaps between replicates [21]; Supplementary Table S6. Cover ranges from 9.67% to 69.67%. We retain the decimal coordinates as printed, without assuming an unreported coordinate reference system. Exact survey days, replicate-level outcomes, contemporaneous temperature and repeat visits are unavailable. This is one survey at ten spatial stations, not thirty independent treatment observations. The January survey cannot automatically serve as a preintervention baseline because local package contracts began in 2021 and the reef-level activity timeline is unresolved.

The Coral Triangle Center (CTC) monitoring series is also distinguished from the inherited CoralNet series. The 17–23 October 2022 CTC survey used point-intercept transects (PIT) at 3 and 10 m and trialled photoquadrats on the same transects with ReefCloud [22]. CTC reports thirteen monitoring sites in November 2023 and fourteen in 2024 [23, 24]. The 2023 account describes hard-coral cover as 6.2 percent higher without resolving relative versus percentage-point change. No cover level is reconstructed from that statement. The 2024 resilience scores are not coral-cover percentages. Programme-level protocol descriptions are not copied into individual CoralNet visits without a verified identity crosswalk.

Intervention histories also identify CTC's Adopt-a-Coral activity in Ped from 2020, expansion to Mangrove Point in July 2023, and a separate demonstration-site expansion in Toya Pakeh and Ped in early May 2025 [25, 26]. These records document overlapping conservation activity, without establishing financial overlap with COREMAP. They are retained as potential competing interventions. The February 2023 GP5 monitoring activity [27] provides a follow-up event, but no additional numerical survival endpoint is recovered from that account.

Documented restoration progress

Implementation reports describe 100 of 200 reef stars reported restored at Ped, 42 fish domes constructed at Suana, and mask-point structures at Lembongan during January–June 2022 [28]. The 2023 procurement tables connect coral-restoration materials and beneficiaries to GP4 and GP5 [29]. These records improve activity attribution but provide neither itemized restoration payments nor georeferenced as-built boundaries. Gili Matra's ten locations were still described as planned in the mid-2022 report; this count is not treated as completed restoration.

Repeated station histories and project baseline locations

The Gili Matra management plan reports underwater photo-transect (UPT) cover for sixteen station identifiers in 2014, 2019, 2020 and 2021 [30]. Of 46 nonmissing station-years, 38 fall within 2015–2025. Station counts are thirteen in 2019 and 2020 and twelve in 2021. Ten identifiers have all three years (Supplementary Table S8), with equally weighted means of 26.799%, 36.508% and 48.355%. This composition check retains uncertain survey dates, depths, coordinates and transect placement. Repeated identifiers do not confirm identical transects or identify treatment effects.

The management plan reports a 2021 network mean of 48.46%, whereas the project completion table reports 21.69% for Gili Matra [19, 30]. Both values are retained with their own provenance because their sampling frames and definitions have not been reconciled. We do not replace one with the other or splice the two series. The discrepancy materially limits ecological attribution at protected-area scale.

The Gili Balu initial environmental examination supplies eight baseline records linked to proposed mooring-buoy sites, with reported coordinates, cover and depths [31]. Two pairs repeat exactly the same source coordinates despite different cover or depth entries. One depth is printed as 154 m; its literal value is retained but excluded from analytical depth fields. Nearest-neighbour screening against the ten January 2022 survey stations gives approximate separations of 162–1,691 m.

Even the nearest Kenawa candidates differ in reported depth, 15–20 m versus 7–8 m. These are project-linked infrastructure baselines, not verified restoration polygons or matched repeated transects. No ecological outcome or heat exposure is filled from the nearest point.

Post restoration observations and source reconciliation

An open SD Point workbook contains 30 photoquadrats, twelve fish-video records and 140 tile-face records from seventy recovered tile pairs [32, 33]. Raw hard-coral means are 48.20%, 34.60% and 13.483% for natural, restoration and rubble habitats: restoration exceeds rubble by 21.12 percentage points and is 13.60 below natural habitat (Supplementary Table S13). All 30 retained cover values agree with the original workbook. Recomputed standard errors match the article after rounding; the midpoints of its natural and restoration intervals match the raw means, despite different means in the article text (Table 3; Supplementary Table S15). The cause remains unconfirmed. Both representations are retained, including the article-based restoration–rubble contrast of 20.58 percentage points. Each habitat has one locality; tile recovery intervals are not repeated pre-restoration transects. These spatial contrasts do not identify restoration effects, and the financial link to GP4 remains unverified. Figure 3 presents the expenditure record alongside ecological distributions at their respective sampling scales.

Table 3
Reconciliation of post restoration hard coral cover

Habitat	Quadrats	Raw mean %	Article mean %	Difference pp
natural	10	48.200	40.20	8.000
restoration	10	34.600	34.06	0.540
rubble	10	13.483	13.48	0.003

Sources [32, 33]. Each habitat has one locality. The raw–article mean differences of 8.00 and 0.54 percentage points remain unresolved. Recomputed standard errors and the published interval midpoints support an internal consistency diagnosis (Supplementary Table S15), not a correction of the article or a treatment-effect estimate.

Two-province validation and publication timing

We recover 48 published star-rated hotel occupancy values covering 24 months in each of Bali and West Nusa Tenggara during 2024–2025 [34, 35]. This separate outcome measures provincial accommodation activity, not domestic visits or marine recreation. A no-tuning seasonal baseline, predicting each 2025 month with the corresponding 2024 value, has MAE 2.624 percentage points in Bali and 3.212 in West Nusa Tenggara, with RMSE 3.507 and 3.910 (Supplementary Table S4; Fig. 4a,b). All twelve targets per province are retained. This is a retrospective benchmark with current retrieved vintages, not a replication of the Bali visitor ridge model or a causal multi-destination test. Gili Matra and Gili Balu share one provincial tourism series and do not add two independent tourism outcomes.

For the 24 hotel observations in 2025, the earliest dated releases located are 31–67 days after month-end, with median 33 days. January values appear in the joint 8 April release; the May West Nusa Tenggara value was recovered from the 1 August June report. These are observed release dates and upper bounds on first availability, not certified first releases. Current webpage snapshots cannot verify unchanged historical values. These hotel release dates are not assigned to the separate Bali visitor series.

An additional sensitivity analysis retains the original 24 Bali visitor targets and ridge penalty of 10, but delays both nonseasonal predictors and the latest training target by two or three months (Supplementary Table S5). At two months, MAE is 126,887 visits for the history model and 131,138 for its thermal extension; at three months, it is 129,268 and 140,997. The unchanged seasonal baseline remains 80,394. All scenarios are reported. These computations test assumed

delays rather than reconstructing operational forecasts, and they do not establish the absence of thermal or financial effects.

Marine tourism receipts at protected area scale

Kupang National Marine Conservation Area Office (BKKPN Kupang) financial statements provide 2023 and 2024 marine nature-tourism receipts for Gili Matra and six other protected areas [36, 37]; Supplementary Table S7. Gili Matra domestic plus foreign person-ticket receipts rose from IDR2,062,920,000 to IDR3,425,250,000, an increase of IDR1,362,330,000 (66.04%). Foreign-ticket receipts account arithmetically for 99.77% of this increase (Supplementary Table S13). Equipment, education and research charges are excluded. Fourteen of sixteen area-year rows have both person-ticket components; source blanks remain missing. These are nominal administrative receipts, not visitor counts or net business income. Other areas extend descriptive coverage without supplying certified untreated controls.

The statements attribute revenue changes partly to full tariffs from 21 December 2023 and expanded service posts [36, 37]. Consequently, a change in receipts can reflect visitor numbers, visitor composition, prices or collection coverage. We do not divide receipts by an assumed tariff or estimate project effects from these two annual observations. The 2023 statement bears a 10 January 2024 signature and the 2024 statement a 7 May 2025 signature; neither date proves public release of the current file. The Gili Balu study was published on 19 December 2024 after its January 2022 survey, illustrating why observation time and information availability must be stored separately.

An additional official report records Gili Matra service revenue of IDR1,320,500,000 for January–June 2024 [38]. Monthly and regional sums each reconcile to jurisdiction-wide receipts of IDR1,638,880,000 (Supplementary Table S16). The jurisdiction issued 13,212 authorizations: 13,181 tourism tickets, 31 research permits and no education permits. Service revenue covers multiple conservation-area activities and remains separate from person-ticket receipts. Authorizations do not measure destination-specific unique visitors, and half-year values are not annualized. Figure 4 separates provincial hotel activity from the Gili Matra person-ticket comparison.

Historical island accommodation guests

The Gili Matra management plan reports domestic and foreign accommodation guests on Gili Air, Gili Meno and Gili Trawangan during 2011–2019 [30]. All twenty-seven island-years are retained, including fifteen in 2015–2019 (Supplementary Table S9). These counts cannot be joined directly to entrance-ticket revenue or treated as reef users. The 2018 reported total of 562,501 differs by one from its component sum; both are preserved. For ten dive locations, printed latitude and longitude headings are reversed relative to numerical degrees. Original columns and a separate geographic interpretation are retained; no dive endpoint is assigned to a UPT station.

Local attraction records across the intervention period

Official 2024 and 2025 tourism workbooks supply 140 source cells for Nusa Penida, Tulamben, Padangbai and Jemeluk; all 64 overlapping cells agree [39, 40]. Retaining the latest place–year–category entries gives 76 cells in 44 place-years spanning 2015–2025. Unlabelled early columns, category-specific dashes and numeric zeros remain distinct. Tulamben has positive domestic and foreign entries throughout 2019–2025; Padangbai has a comparable-category window in 2020–2025, with 2019 domestic visits missing (Table 4). These records do not identify diving participation or untreated controls.

Table 4
Local attraction visits and category availability

Year	Tulamben domestic	Tulamben foreign	Padangbai domestic	Padangbai foreign
2019	3,604	35,429	Missing	14,043
2020	398	6,201	11	1,858
2021	238	269	46	87
2022	2,461	12,289	187	3,350
2023	3,297	25,242	19	7,452
2024	1,245	8,603	42	2,689
2025	1,780	57,311	2,970	5,230

Sources [39, 40]. These are administrative attraction visits, not identified diving trips. All four destinations, earlier unlabelled columns, zeros and missing values remain in the evidence workbook. Complete positive categories do not establish unchanged collection methods or eligibility as untreated project controls.

Modeled economic benefits and their assumptions

The completion report estimates an economic net present value of US$126.85 million and an economic internal rate of return of 17.83%, using a 9% discount rate across twelve MPAs and both project phases [19, Appendix 9]. Its annual tourism values are US$3.53 million with the project and US$0.82 million without it, a modeled difference of US$2.71 million. Without-project values use stakeholder-informed proportions rather than observed controls. These estimates include projected benefits and exceed the scope of the six local packages. Conflicting sensitivity figures and unreconstructed annual cash flows prevent independent validation of the reported returns (Supplementary Table S14).

Project evidence and competing explanations

The project evidence supports different pathway stages (Supplementary Table S11). GP4 has package-linked materials and village-level installation, GP5 has implementation and short-term survival in the same reporting chain, and GP6 lacks a verified intervention–outcome join. Missing denominators and source dependence restrict ecological attribution.

Gili Matra common-station means increased in 2019–2021, before the reported October–December 2022 GP5 transplantation; the earlier rise cannot result from that later activity. Earlier programme effects, overlapping Ped initiatives and survey differences remain unresolved. Gili Matra receipts cover only postimplementation years. These are documentary checks, not statistical placebo tests (Supplementary Table S12).

Discussion

The evidence supports destination-level accounting of conservation expenditure and separate descriptions of ecological condition and tourism activity. It does not connect these measurements closely enough to estimate financial protection against thermal stress. This distinction is substantive: the six local packages have a reconciled cumulative expenditure total, but none supplies a verified restoration-specific cost linked to the same ecological units before and after implementation. Financial traceability at package level is therefore stronger than ecological attribution at intervention level.

The tourism records show why economic recovery and ecological persistence require separate interpretation. Bali domestic visits rebounded toward the 2019 total, while local attraction series and protected-area receipts measure different activities and collection processes. Province-level visits do not identify reef use, and changes in entry receipts also depend on tariffs and collection coverage. Combining these outcomes into a single resilience index would obscure their definitions. Their

contribution here is to reveal the scales at which tourism activity can be observed and the restrictions on comparing those scales.

Local valuation studies address another part of the financing pathway. A Gili Matra contingent-valuation study elicited willingness to pay and willingness to accept among tourists, businesses and fishing households [41]. These stated preferences inform prospective financing, rather than measuring collected fees or realized project benefits. A subsequent travel-cost study also examines marine tourism value [42]; its publisher abstract informs context only, without importing unverified numerical estimates or extending the 2015–2025 observation window. Preference values, receipts and modeled ecosystem-service benefits are therefore kept separate (Supplementary Table S17).

Financial evidence has an additional attribution problem. Projects can be directed toward damaged locations, and expenditure can be recorded after the activity it finances. A simple negative relationship between investment and environmental condition could then reflect targeting, while a positive relationship could reflect selection of already successful destinations. Identifying financial additionality requires the intervention date, a plausible comparison group and evidence about the untreated trajectory. Even a convincing tourism treatment effect would not establish ecological mediation if the project also improves infrastructure. The analysis must allow those pathways to differ by project type.

Ecological studies elsewhere motivate locally matched evaluation [3, 4], but cannot supply missing Indonesian counterfactuals. Within this archive, the MPA summaries change in different directions, Gili Matra source means disagree, and the SD Point study has one locality per habitat. These records describe different ecological supports. Treating quadrats as independent intervention sites, averaging incompatible summaries or assigning nearby coordinates would create apparent replication without resolving the treatment comparison. The data do not support estimating a thermal buffering threshold.

The thermal inputs did not improve pooled error in the executed ridge comparison, and the seasonal baseline performed better. This result provides no support for adding these regional thermal features to this particular model and evaluation period. It does not show that temperature is ecologically unimportant or that more local exposure has no tourism association. Historical revised archives and uncertain publication delays also prevent interpreting retrospective errors as operational forecasting performance. Independent destinations, comparable outcome definitions and historical availability records would be needed to assess broader predictive transfer.

The remaining limitations concern linkage and identification. Finance is attributable to destinations and reporting years, and the ecological record now includes station-labelled histories, geolocated surveys and project-linked baseline points. However, exact survey dates, repeated transect identity, as-built restoration footprints and contemporaneous reef temperatures have not been joined. Tourism accommodation counts and protected-area revenue have different definitions and discontinuous coverage. The conflict between published Gili Matra annual means further prevents an unqualified ecological trend claim. These limitations preclude estimating the complete finance–ecology–tourism causal chain from the present evidence.

Project reports support implementation and early biological outcomes; the completion assessment also supplies a positive modeled economic case. These forms of evidence answer different questions. Short-term survival and spatial cover contrasts do not measure additional reef recovery, while entrance receipts do not measure net local income. Fees paid by visitors and received by authorities cannot be counted twice as social benefits. Net tourism benefit requires a defined perspective, incremental resource costs and a counterfactual; ecological net benefit requires additional condition or function over an explicit area and duration, accounting for displaced damage or donor losses where relevant. No benefit–cost ratio is calculated by dividing twelve-area modeled benefits by six-package spending.

Methods

Study area and observational support

The target observation period is 2015–2025. Project records concern Nusa Penida in Bali and Gili Matra and Gili Balu in West Nusa Tenggara. Ecological units range from named stations and photoquadrats to protected-area summaries. Tourism units include provincial months, attraction years and protected-area receipt years. The environmental archive represents the NOAA East Java and Bali regional virtual station. Analyses retain these different observational units; calendar overlap and a shared place name do not establish a valid ecological or causal join.

Nusa Penida GP1/GP4, Gili Matra GP2/GP5 and Gili Balu GP3/GP6 are distinct intervention bundles. Destination identifiers enable report-level matching but do not establish treatment at every reef within a protected area. Shared package GP7 is excluded from local expenditure intensity. No national panel is constructed from these seven contracts.

Source selection and analysis units

This is a targeted integration of public records for the specified destinations, not a systematic review or a probability sample of Indonesian conservation projects. The retained archive combines official project and management reports, official tourism tables, published ecological studies and their accessible data, and previously audited image annotations. Sources were used for the measurements they explicitly report. A report date, destination name or nearby coordinate alone was insufficient to establish treatment exposure. No exhaustive search denominator or estimate of national project coverage is claimed.

The finance unit is a package and accounting interval; the exposure unit is a regional day or month; ecological units include survey stations, image visits and within-site samples; tourism units include province-months and destination-years. Repeated records from the same destination are not additional independent projects. Supplementary Table S10 specifies the support and permissible comparisons for each principal module. Analysis-specific denominators replace a single pooled sample size. Only the tourism and regional thermal series are matched by calendar month for the predictive benchmark, with their geographical mismatch retained.

Data sources and tourism measurement

The tourism component covers Bali Province, while the environmental archive represents the broader East Java and Bali region. Bali's provincial visitor total is an economic activity indicator and not a sample of reef visitors. It includes domestic visitation associated with activities beyond the marine environment. The provincial visitor benchmark does not combine domestic and international counts, infer unique people from visits, or use hotel occupancy as an interchangeable outcome. Neither provincial tourism nor the regional ocean summary determines the geography of a future project-effect analysis.

The BPS page embeds the historical table in its HTML payload. We preserved the retrieved page and metadata, decoded the embedded table, located explicit year and month headers and extracted integer counts for 2015–2025. Blank future-year columns were left outside the target period and were not converted to zero. Eleven published annual totals were preserved as source observations and compared with independently summed monthly values. The original provider is the Bali Government Tourism Office survey, disseminated by BPS [13]. The preserved webpage snapshot is a current historical vintage; publication dates for individual monthly observations and a complete survey-method history have not been reconstructed.

Project finance and ecological linkage

We manually transcribed and visually checked the Q4 2021 payment table, the Q4 2022 annual-disbursement table and the Q4 2022 cumulative package table [15, 16]. Each record retains package identifier, destination, currency, accounting stage, date or reporting interval, source page and retrieval hash. For package p, C(p,2022) is checked against the sum of dated 2021 payments plus reported 2022 disbursement. This equality holds exactly in nominal IDR for all seven packages. Published USD totals with inconsistent accounting scope or typographical discrepancies are flagged, not reconciled through an assumed exchange rate. Zero is not substituted for unavailable 2023 site-level spending.

Ecological sources are stored separately as MPA-year cover, GP5 fragment survival, inherited CoralNet image-point proportions and the January 2022 Gili Balu station summaries. No conversion is attempted between outcomes. The ten new coordinates are transcribed from the published station table; depth and replicate design come from its Methods. A diagram showing 25 m conflicts with the 50 m Methods description, and later prose claiming cover above 60% at Belang Selatan conflicts with the explicit 57% abstract estimate. We retain the explicit numerical estimates and written methods while recording both inconsistencies. No exact date, coordinate reference system, temperature or within-station repeat observation is invented. The original CoralNet missing position and exposure fields remain unchanged.

For release timing, we record the observation month, date printed on the retrieved BPS page, exact source URL and whether a number occurs in its target-month report or a later retrospective comparison. The difference between observation-month end and that dated report is calculated in days. Dates embedded in an ICCTF file URL are not accepted as proof of first publication. Financial and ecological reports retrieved after the outcome period can support retrospective description but are not automatically admissible predictors at historical forecast origins.

Marine entrance receipts are transcribed by protected area, year and fee category from the financial statements. Domestic plus foreign ticket receipts form a transparent person-ticket revenue subtotal only when both entries exist; equipment and non-tourism charges are excluded. Published column totals are checked independently without rewriting source blanks as zero. Revenue is nominal IDR, not project spending or visitor counts. Source signature dates, dated news posts, journal publication dates and retrieval dates occupy distinct fields. A current source snapshot is never assumed to have existed unchanged at its signature date.

The 2024 second-quarter management report was transcribed separately by jurisdiction or destination, reporting period, receipt scope and source locator [38]. Table 5 and Figs. 7–9 were visually checked. Monthly and regional sums were compared with the half-year total, and permit categories with the reported aggregate. A regional dash remains missing; July–December dashes denote periods outside this report. Repeated aggregates are retained for reconciliation, not counted as independent observations. No aggregate is allocated to a project or converted into visitor numbers. The current download does not certify first publication.

For the historical station table, every original blank remains missing. Source annual means are retained and independently compared with arithmetic means of available station summaries. The common-ID subset includes station identifiers 1, 3, 5, 6, 7, 8, 9, 10, 12 and 13, selected only because each has nonmissing values in 2019, 2020 and 2021. These summaries are equally weighted across stations and do not reconstruct unknown transect-level sample sizes. The 2014 values remain outside the target period as historical context. No inference of project effectiveness is based on these descriptive averages.

Reported degree–minute–second coordinates are converted to decimal degrees in separate fields. Candidate distances use the haversine formula with a spherical radius of 6,371,008.8 m, treating the reported coordinates as geographic degrees while retaining datum uncertainty. Distances screen potential links and do not establish treatment membership. For the water-temperature archive, raw row numbers and duplicate flags are added without deleting, averaging or shifting observations. Missing timezones and missing reef deployment depths remain explicit. Management-plan dates and download-path dates do not establish initial public availability; these sources remain retrospective evidence.

Additional source reconciliation

The original five-sheet SD Point workbook is retained [32, 33]. All 30 hard-coral observations were compared directly with the retained CSV, and habitat means and sample standard errors, s/√n, were recalculated without normalizing row totals. We checked published interval midpoints against raw and reported means; this does not reconstruct interval methods or create new confidence intervals (Supplementary Table S15). The earlier dataset version is retained without assuming it explains the disagreement. Tile keys comprise site, recovery week, replicate and face; paired faces are not independent deployments. Exact sample dates and temperatures remain unfilled.

For each official attraction workbook we preserve vintage, sheet, source cell, year, category and literal value [39, 40]. Overlap checks compare cells with the same place–year–category key. Unlabelled early columns are not assumed to be total visitation. Numeric source zeros remain zero in the raw table, with unresolved semantics flagged. A separate conservative summary adds domestic and foreign values only when both are positive; this is a descriptive eligibility rule, not a fitted model or proof that excluded zeros are invalid. The current listing date does not establish historical first availability.

Completed environmental processing

The full NOAA text snapshot downloaded on 8 October 2026 was preserved with its SHA256 hash. We filtered daily dates to the target interval, checked uniqueness, compared observed dates with the complete calendar and required finite source values. We checked the representative SST against broad physical bounds and required nonnegative HotSpot and DHW. These checks establish numerical integrity within this archive, not independent satellite accuracy or ecological validity. All 132 calendar months have complete daily coverage [10, 11].

For month m containing D_m days, SST_m and SSTA_m are arithmetic means of the corresponding daily regional statistics. DHWmax_m is the maximum published daily DHW. HSdays_m counts days with HotSpot ≥ 1°C. Annual means weight the monthly mean by D_m; annual DHW is the maximum of monthly maxima; annual HotSpot days sum the monthly counts. We independently reproduced the annual summaries directly from daily records. The workbook preserves monthly inputs and transparent annual formulas. Changes to a test input, a missing value and a valid zero were checked separately before restoring the source value.

No inferential test was applied to annual maxima or selected peak years. They are descriptive properties of the retrieved record. No ecological damage fraction is derived from DHW. The historical archive is a current snapshot rather than a set of contemporaneous publication vintages. Future predictive use must therefore be identified as retrospective unless historical availability is separately reconstructed.

Missingness and version control

The source registry distinguishes verified source observations, verified derivations, inherited observations, unavailable inputs and proposed analyses. Unavailable amounts remain missing, and source-reported zeros are retained with their interpretation flags. No interpolation, forward filling or allocation by population or coastline was applied. The source-specific tables retain their own units and coverage; they were not combined into a balanced national panel. The conservative positive-category tourism summary selects observations and is not a correction for missingness or an assumption that genuine zero visitation cannot occur.

The broader provincial gross regional domestic product and older hotel modules were not independently recovered for this manuscript and are excluded. The thermal, visitor and prediction files are retained with their provenance. The 147 CoralNet visits are inherited observations rather than new collections. Contradictory totals, ambiguous area units and unverified release dates remain in the issue register. Missing fields are not replaced by interpolation, geographical allocation of shared expenditure or candidate offshore-grid values.

Retrospective prediction

The secondary task predicts the next Bali domestic visitor count from earlier observations. The seasonal naive forecast equals the count twelve months earlier. The first ridge model uses log(1 + visits) at lags one and twelve and eleven calendar-month indicators. The second uses the identical design plus previous-month representative SSTA and maximum DHW. These two exposure variables were chosen before calculating comparison results. They are not contemporaneous target-month observations. We fit the log-transformed target with an unpenalized intercept, training-only centering and scaling, and a squared-error objective plus a ridge penalty on standardized coefficients. Predictions are transformed with expm1 and negative outputs are clipped to zero; no lognormal smearing adjustment is used. The resulting benchmark is not presented as an unbiased conditional-mean estimator.

Supervised fitting starts in January 2016 because a twelve-month lag is required, leaving 48 initial training target rows through December 2019. Each ridge model independently chooses its penalty from 0.01, 0.1, 1, 10 and 100 by minimum MAE over 48 expanding-window development origins in January 2020–December 2023. A smaller penalty resolves an exact tie. Selected penalties remain fixed during the 24 evaluation origins in January 2024–December 2025. Coefficients and scaling are refitted monthly using only earlier targets. This protocol was recorded before running the comparison but after examining source records; it is not preregistered or an untouched external test. All comparisons use the same observations and input-release assumption.

MAE is the primary metric and RMSE is secondary. For each origin, the seasonal scaling denominator is the mean absolute twelve-month difference in the raw training visitor history. MASE averages the absolute prediction error divided by that origin's training denominator [14]. Each denominator is positive. Scores are reported for 2024 and 2025 separately and pooled. Prediction records, development-grid scores and exact settings accompany the manuscript. The pandemic and subsequent rebound occur in model development, which may affect selected penalties and the relevance of training patterns to later years. We do not retune on the evaluation outcomes or interpret these scores as a stable ranking across regimes.

The analysis assumes that the immediately preceding month's visitor and thermal values are known. Their actual publication delays and historical vintages were not verified; retrospective results cannot establish operational performance. Future extensions should reconstruct availability, evaluate alternative outcome definitions and more closely matched oceanographic exposure, and use additional independent destinations before testing flexible learners. Uncertainty in model comparisons would also require a method respecting temporal dependence and a larger evaluation sample. No project treatment effect, mediation model or thermal causal effect is estimated here.

Added validation and availability sensitivity

The hotel extension fixes a seasonal naive specification and uses every month of 2025 in each of the two provinces; no tuning, pooled regional regression or thermal covariate is used. MAE and RMSE are in percentage points, calculated separately by province. The 2024 inputs are partly recovered from later year-on-year comparisons, so this remains a retrospective current-vintage exercise. Its purpose is to test data comparability and establish a simple benchmark before any more flexible multi-destination model.

For the Bali visitor sensitivity, L is fixed in turn at 1, 2 or 3 months. The nonseasonal visitor feature and both thermal features use $t - L$; the seasonal feature remains $t - 12$. At target t, supervised training includes targets from January 2016 only through $t - L$, and centering, scaling and coefficients are recomputed from those rows. Thus the exercise delays both inputs and training labels. The original penalty of 10 is frozen for both ridge variants and is not retuned to the test outcomes. All scenarios use January 2024–December 2025 targets; $L = 1$ reproduces the original predictions numerically. No assumed-delay scenario is labeled a historical-vintage backtest.

Assessment of project contribution

We assessed whether the archive supported specific steps from funding to activity and observed response. For each restoration package, we recorded financial attribution, implementation evidence, outcome linkage, source independence and competing explanations. A link required an explicit package or activity correspondence; similar place names were insufficient. Reports from the same implementing or reporting chain were treated as related evidence, rather than independent replications. No numerical evidence score or probability of causation was assigned.

We checked whether candidate outcomes preceded the specified activity, whether monitoring units were comparable, and whether other interventions or measurement changes could explain the observation. Unknown alternatives remained unresolved. These checks assess the plausibility and boundaries of a contribution claim; they do not estimate the untreated outcome. Statistical negative controls, interrupted time series and matched causal comparisons were not performed because corresponding treatment assignments, controls or comparable local time series were unavailable. The absence of underwater temperature alone was not treated as a universal barrier to project evaluation; treatment definition and valid comparison remain the primary identification requirements.

Ecological and tourism benefit accounting

We distinguish observed outcomes, descriptive contrasts, source-modeled benefits and causally additional benefits. Hard-coral cover means were recalculated from ten raw quadrats per habitat without treating subsamples as independent project replicates. Revenue change equals 2024 minus 2023 person-ticket receipts; percentage growth divides by the 2023 subtotal. Domestic and foreign components reconcile exactly to the total change. No confidence interval or causal coefficient is attached to these arithmetic contrasts. Nominal receipts are not deflated or converted to visitor volumes because a validated fee and visitor-mix series is unavailable.

For the completion-report model, we transcribed the geographical scope, horizon, discount rate, with-project and without-project values and reported returns, and checked displayed arithmetic and narrative–table consistency. We did not reconstruct the economic internal rate of return or economic net present value without annual cash flows. Source modeling assumptions remain labeled as assumptions; no modeled benefit is added to the observed panel. Ecological additionality, financial net income and social net benefit are separate endpoints. Tourism fees, business revenue and ecosystem-service valuations are not summed without resolving overlap and whose benefits and costs they represent. This is a benefit-accounting audit, not a new economic appraisal.

Targeted literature updates distinguish inspected full texts from abstract-only leads. The Gili Matra stated-preference study was checked against its methods and Table 1 [41]; no respondent-level data were obtained and no published regression was refitted. The travel-cost study contributes only its verified abstract-level method description [42]. A repository thesis with restricted full text was retained in the source register but excluded from quantitative synthesis. This targeted update is not an exhaustive systematic review.

Computational verification

The original benchmark was rerun in an isolated output directory from the archived monthly visitor and thermal inputs without changing the penalty grid, features or evaluation months. All 72 model-month predictions, ten development-grid scores and nine model-period summaries were compared with the archived outputs using an absolute tolerance of 10^{-6} for numerical values. MAE, RMSE and MASE were additionally recomputed directly from the stored prediction errors and scaling denominators. These checks assess numerical reproducibility; they do not validate historical availability or geographical exposure. The verification receipt records input hashes and the runtime version.

Use of AI assisted tools

OpenAI ChatGPT and Codex assisted with source discovery, document drafting, data extraction and preparation of analysis and validation code. Their use is documented here because it extends beyond language editing. Source files, extracted values, calculations and unresolved discrepancies are retained alongside the analyses for verification.

Ethics and data reuse

This study reanalyses public administrative records, published ecological measurements and previously audited image annotations. It reports no new human-participant recruitment, collection of identifiable participant data or experimental intervention on animals.

Declarations

Data Availability

The compiled evidence archive contains source URLs, retrieval hashes, financial transcriptions, ecological records, tourism observations and matching decisions. Public source locations are cited in the reference list. SD Point study data are available at https://doi.org/10.6084/m9.figshare.28737785 [32], and historical Gili Air harbour measurements at https://doi.org/10.1594/PANGAEA.924083 [43]. The accompanying Supplementary Information documents source comparisons and limitations. The compiled archive and additional consistency checks are retained locally; a public accession and a complete submission-ready supplementary data deposit have not yet been finalized. Current source snapshots do not certify historical release vintages.

Code Availability

The retained research package includes scripts for reconstructing the monthly series, retrospective prediction, financial reconciliation, ecological consistency checks and publication-delay sensitivity analyses. The figure package contains plotting code and its input tables. Input hashes and computational verification records accompany the local archive. A permanent public code repository has not yet been assigned.

Author contributions

Y.L. contributed to the conceptualization, methodology, data collection, formal analysis, and writing of the original draft. F.H. contributed to supervision, validation, review and editing, and project administration. All authors reviewed and approved the final manuscript.

Additional Information

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Competing interests

The authors declare no competing interests.

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Figures

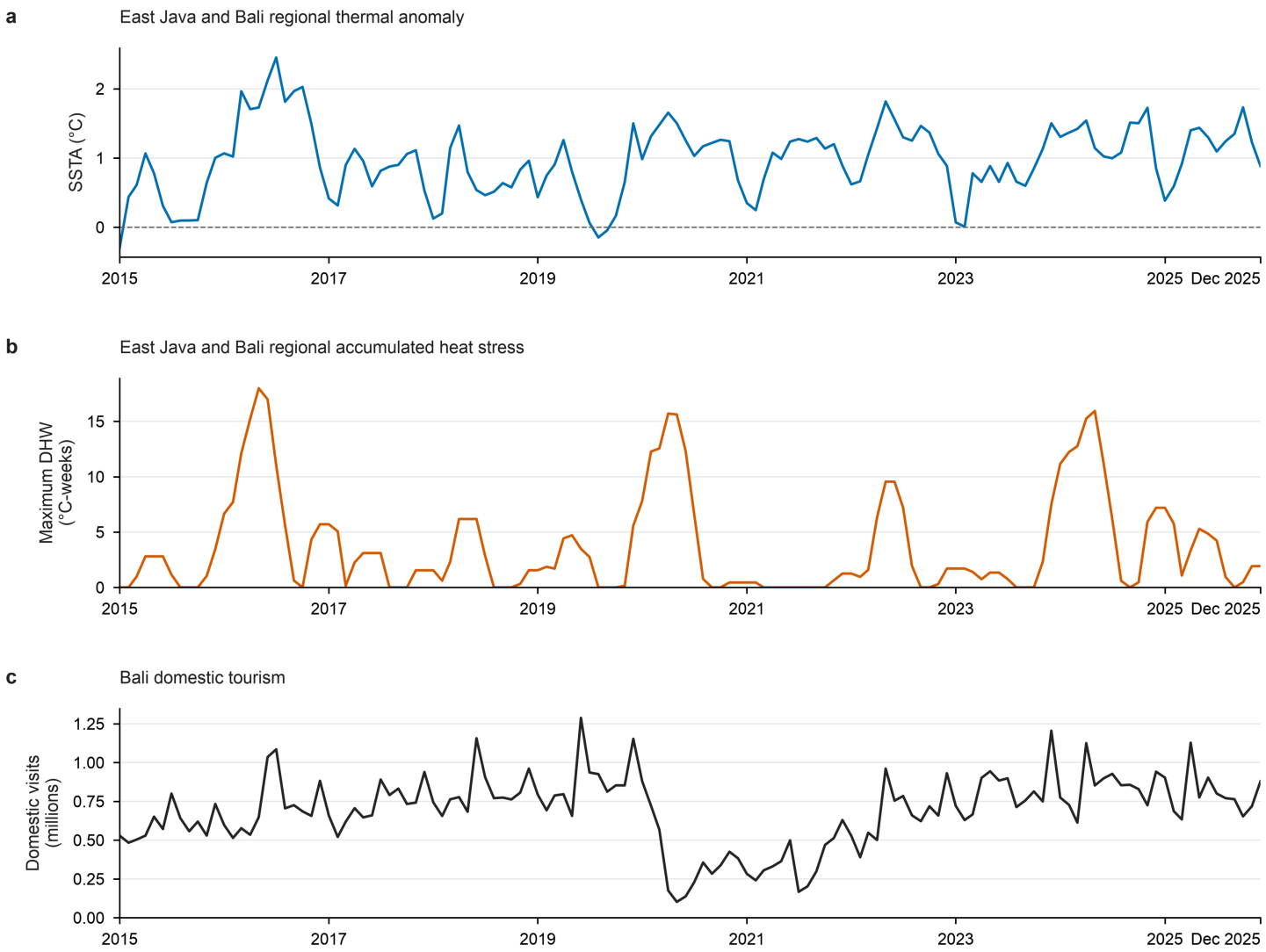


Figure 1

Regional thermal exposure and domestic tourism over 2015–2025. a, Monthly means of daily representative sea surface temperature anomaly (SSTA). b, Monthly maxima of daily degree heating weeks (DHW). Both thermal series describe the NOAA East Java and Bali regional virtual station [10, 11]. c, BPS Bali domestic visits [13]. Each panel contains all 132 months; no interpolation is applied. Panels share a calendar, not identical geography. Their juxtaposition does not establish bleaching, tourism effects or marine heatwave event duration.

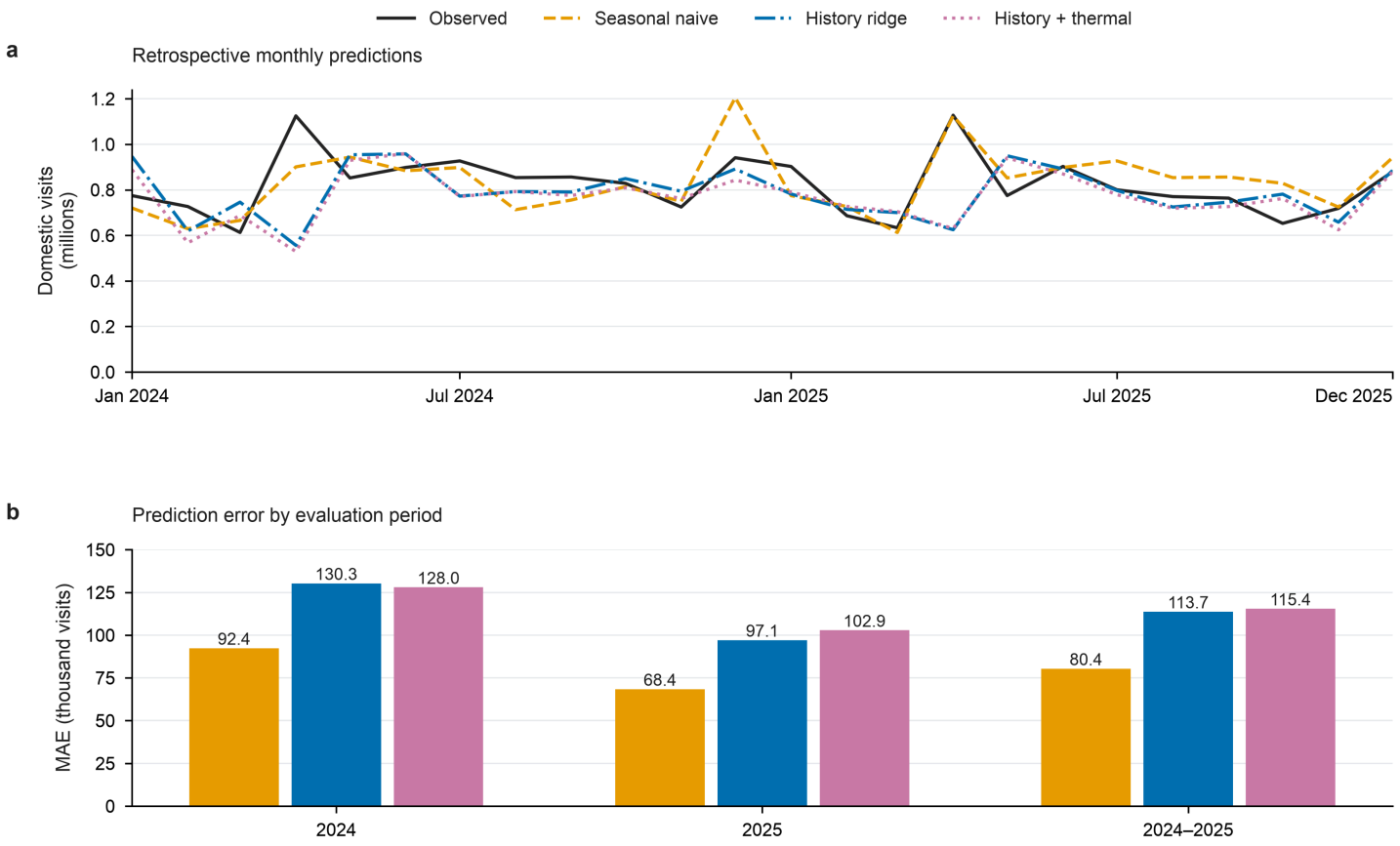


Figure 2

Retrospective prediction performance for Bali domestic tourism. a, Observed monthly counts and three retained predictions over all 24 evaluation months in 2024–2025. b, Mean absolute error (MAE) for each evaluation year (12 months each) and the pooled period (24 months). Both ridge variants use the previously selected penalty of 10; the thermal variant adds previous-month SSTA and DHW. MAE follows the error definition in [14]; predictions retain the archived estimates. No error bars are shown because no uncertainty intervals were estimated. Historical publication vintages are unverified; these are retrospective comparisons, not operational or causal evaluations.

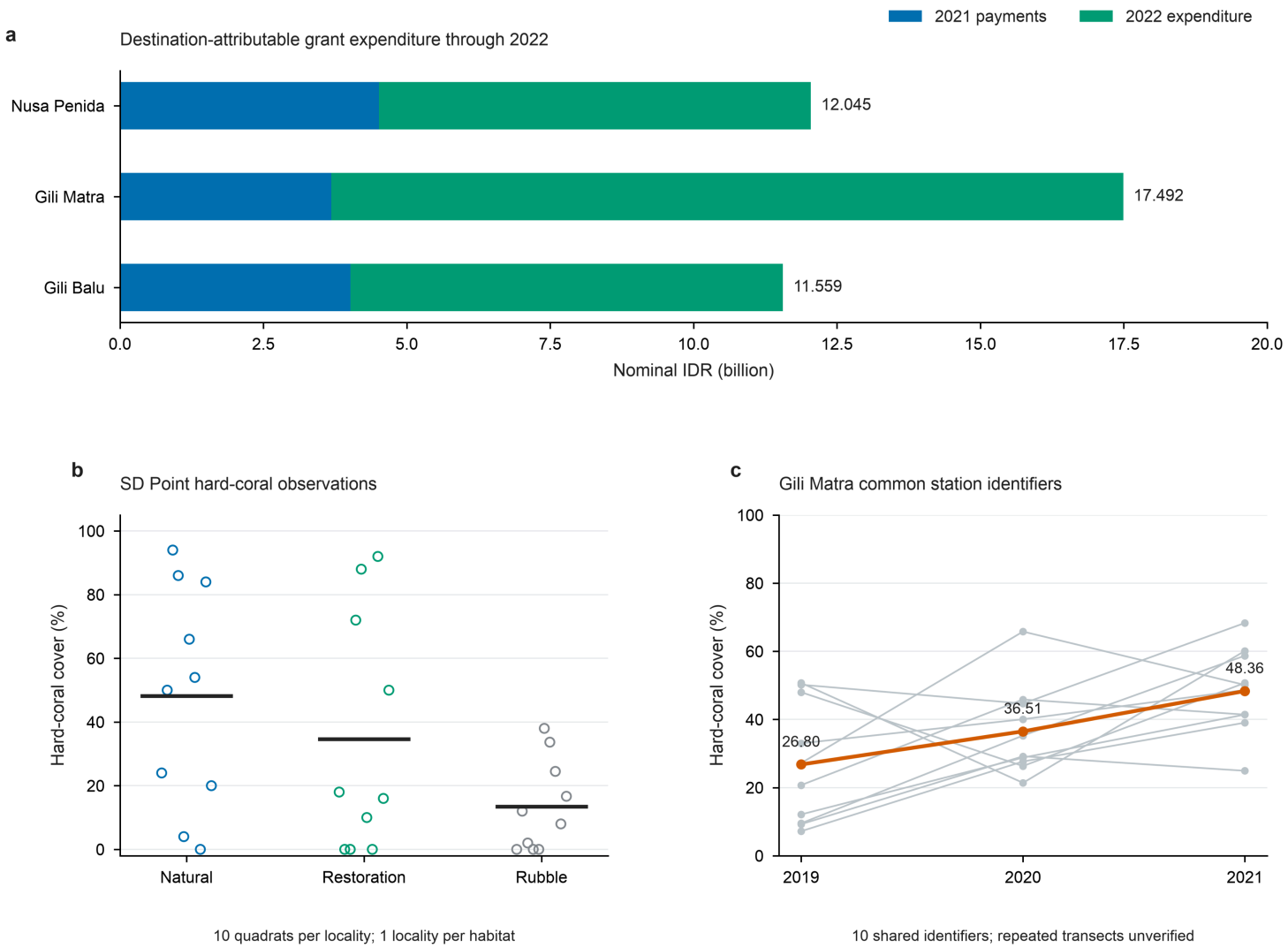


Figure 3

Project expenditure and ecological observations at distinct sampling scales. a, Nominal 2021 payments and 2022 expenditure for six destination-specific packages; labels give cumulative totals in IDR billion. Shared GP7 is excluded, and package expenditure is not restoration-only cost [15, 16]. b, All 30 SD Point quadrat observations, with horizontal black bars indicating raw arithmetic means. Horizontal offsets separate points and have no quantitative meaning. There are ten quadrats within each of three localities, with one locality per habitat; locality and habitat are confounded [32, 33]. c, Ten Gili Matra station identifiers observed in 2019, 2020 and 2021; grey lines connect reported identifiers and the orange line shows their equally weighted mean [30]. Exact repeated transects are unverified. These earlier observations precede the GP5 transplantation reported for late 2022. No cross-panel treatment-effect comparison or new confidence interval is implied.

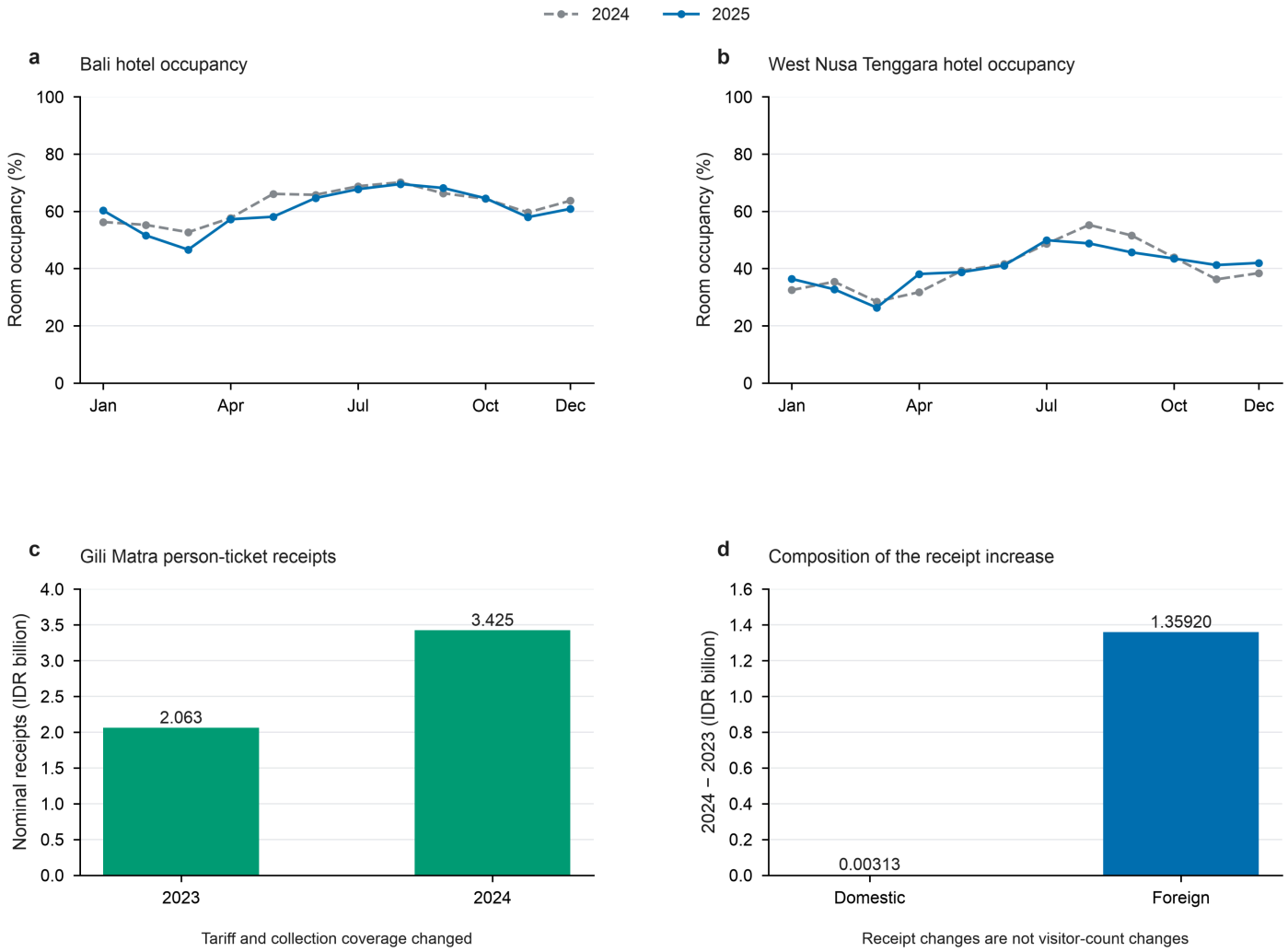


Figure 4

Provincial accommodation activity and Gili Matra tourism receipts. a,b, Monthly star-rated hotel room occupancy in Bali and West Nusa Tenggara. Grey dashed lines show 2024, and blue lines show 2025; the earlier year is the seasonal-naive benchmark for the later year [34, 35]. c, Gili Matra domestic-plus-foreign marine tourism person-ticket receipts in 2023 and 2024. d, Domestic and foreign components of the nominal receipt increase [36, 37]. Receipt definitions exclude equipment, education and research charges. Tariff and collection coverage changed, so revenue growth is not interpreted as visitor growth, net income or a project effect. Provincial hotel measurements and protected-area receipts have different populations and spatial coverage.