



OPERATION-STANDARDIZED SPATIAL AND TEMPORAL ANALYSIS OF MARINE TURTLE INTERACTIONS IN PAKISTAN'S TUNA GILLNET FISHERY IDENTIFIES A ROBUST INTERACTION-PRIORITY AREA

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Purpose, expectation and action intended (select one or more and include corresponding text)

Discussions (for information and open discussion):

The paper is to inform meeting members of the 2012–2019 operation-standardized assessment of marine turtle interactions in Pakistan's tuna gillnet fishery, including temporal trends, immediate release condition and four IOTC 1x1 interaction-priority cells, as set out in Sections 3 and 4.

Feedback (to collect input and suggestions)

The paper is to request review and comments on the interpretation and management application of the four-cell interaction-priority area, including the distinction between fishery-interaction hotspots and biological movement corridors, as set out in Sections 4.6–4.9.

This paper is sharing the analysis of the crew-based observer program based on the datasheet filled/ reported by the fishers for the marine turtles. Also, this paper is reporting bycatch marine turtles on the Pakistan marine region layers and IOTC 1x1 grid.

Conclusion (to record a concluded position or summary)

The paper is to seek confirmation that the identified four-cell area should be interpreted as a fishery-interaction priority requiring independent movement/connectivity evidence before it is described as a biological Blue Corridor, as set out in Sections 4.6–4.7 and 5.

(Based on this analysis pipeline, it will be used to update in future for the identified marine turtles (and others) species-level reporting and reporting for the hotspots and areas-based management on the IOTC 1x1 grid as well as on Pakistan's marine region layers while connecting the dots towards BBNJ areas. The analysis pipeline will be used for other reported bycatch species for shark and rays, seabirds among others based on the same methodology and results)

Recommendation (to ask the meeting to endorse a recommendation)

The paper is to seek endorsement of enhanced zero-inclusive operation-level monitoring in the priority area, improved species verification and electronic monitoring, continued safe-handling/release practice, and independent telemetry, tagging or genetic studies for Blue Corridor validation, as set out in Sections 4.8–4.9.



Abstract

Marine turtle interactions with tuna gillnet fisheries remain an important conservation concern, yet fishery-dependent records can be difficult to interpret when the underlying distribution of fishing activity is not explicitly incorporated. We analysed 2012–2019 data from WWF-Pakistan's crew-based observer programme for the tuna gillnet fishery of the northern Arabian Sea, quantifying temporal variation, biological composition, immediate release condition and spatial structure of marine turtle interactions within a zero-inclusive, operation-standardized analytical framework. The primary rate-model population comprised 30,195 eligible fishing operations, including 845 turtle-positive operations, while 955 definite-capture turtle individuals were recorded in the biological dataset. Operation-standardized interaction rates declined markedly through the monitoring period after adjustment for fishing phase, whereas broad fishing-phase differences were not supported after accounting for year. Species-level interpretation was constrained because 98.0% of captured turtles were reported under the aggregate category "Turtle spp." Among 782 eligible single-turtle events with determined release condition, 3.96% were recorded as released dead, representing immediate condition at release only. Formal spatial hotspot analysis on the IOTC 1×1 lattice identified four contiguous cells with significantly elevated local clustering for both turtle-individual burden and turtle-positive-operation occurrence. These cells remained comparatively stable under leave-one-year-out analysis, fishing-method omission, operation and vessel bootstrap resampling, and a secondary reported-net-km effort sensitivity. The resulting connected area represents the strongest internally supported marine turtle–gillnet interaction-priority area within the monitored fishery and provides a practical focus for enhanced monitoring and bycatch mitigation. However, the fishery-dependent evidence does not establish turtle abundance, habitat preference, exact entanglement locations or biological movement connectivity. Independent telemetry, tagging, genetic or other movement-based evidence would be required to determine whether the identified area corresponds to a biological Blue Corridor.

Operation-standardized spatial and temporal analysis of marine turtle interactions in Pakistan's tuna gillnet fishery identifies a robust interaction-priority area

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Abstract

Marine turtle interactions with tuna gillnet fisheries remain an important conservation concern, yet fishery-dependent records can be difficult to interpret when the underlying distribution of fishing activity is not explicitly incorporated. The data from WWF-Pakistan's CBOP 2012-2019 analyzed for the tuna gillnet fishery of the northern Arabian Sea, quantifying temporal variation, biological composition, immediate release condition and spatial structure of marine turtle interactions within a zero-inclusive, operation-standardized analytical framework. The primary rate-model population comprised 30,195 eligible fishing operations, including 845 turtle-positive operations and 955 definite-capture turtle individuals. Operation-standardized interaction rates declined markedly through the monitoring period after adjustment for fishing phase, whereas broad fishing-phase differences were not supported once a year was accounted for. Species-level interpretation was constrained because 98.0% of captured turtles were reported under the aggregate category Turtle spp. Among 782 single-turtle events with determined release condition, 3.96% were recorded as released dead, reflecting condition at release only. Formal spatial hotspot analysis on the IOTC 1×1 lattice, using local Getis–Ord Gi* statistics against conditional Monte Carlo null models with false-discovery-rate correction, identified four contiguous cells with significantly elevated local clustering for both turtle-individual burden and turtle-positive-operation occurrence. These cells remained stable under leave-one-year-out analysis, fishing-method omission, operation- and vessel-block bootstrap

resampling, and a secondary effort-definition sensitivity based on reported net length. The resulting connected area represents the strongest internally supported marine turtle–gillnet interaction-priority area within the monitored fishery and provides a practical focus for monitoring and bycatch mitigation. However, the fishery-dependent evidence does not establish turtle abundance, habitat preference, exact entanglement locations or biological movement connectivity; independent telemetry, tagging or genetic evidence would be required to determine whether the identified area corresponds to a biological migratory corridor.

Keywords

Marine turtles; tuna gillnet fishery; bycatch; fishery interactions; operation-standardized rates; spatial hotspots; IOTC 1×1 grid; Pakistan; Arabian Sea; Blue Corridors

1. Introduction

Marine turtles are long-lived, highly migratory vertebrates whose life cycles connect nesting beaches, coastal foraging grounds and oceanic habitats across national jurisdictions, exposing them to multiple anthropogenic pressures, including incidental capture in gillnet, longline and trawl fisheries (Wallace et al., 2010; Wallace et al., 2013). Fisheries interactions with marine megafauna are also strongly structured in space, producing areas where fishing activity and vulnerable species overlap disproportionately (Lewison et al., 2014). This spatial and temporal heterogeneity has important consequences for interpreting fishery-dependent turtle records: the number of turtles recorded in an area does not by itself indicate interaction risk, because observed counts are partly determined by the amount and distribution of fishing activity. Meaningful bycatch assessment therefore requires turtle interactions to be interpreted relative to an appropriate measure of fishing exposure, an approach also emphasized by large-scale analyses of marine turtle interactions in tuna fisheries (Domingo et al., 2025).

This requirement is particularly relevant in the Indian Ocean, where information on marine turtle interactions with fisheries has historically been geographically uneven (Wallace et al., 2013). IOTC Resolution 12/04 requires Contracting Parties and Cooperating Non-Contracting Parties to collect and report information on marine turtle interactions and mortality and establishes provisions for handling and release within the IOTC area of competence (IOTC, 2012). Pakistan's tuna gillnet fishery operates across coastal, shelf and offshore waters of the northern Arabian Sea, creating opportunities for interaction between fishing operations and protected marine megafauna. WWF-Pakistan established a crew-based observer programme (CBOP) in 2012 in which trained vessel skippers recorded fishing activity, catch, bycatch, sightings and release information, supporting the development of safe-handling and release procedures for marine turtles and other protected taxa (Abdul Razzaque et al., 2020), and the trials of electronic monitoring to complement crew-based observation (Abdul Razzaque et al., 2024b).

Previous analyses from this monitoring programme illustrate both the value and the limits of crew-based data. A spatiotemporal assessment of dolphin bycatch showed substantial temporal and spatial heterogeneity and emphasized the need to consider operational and temporal structure when interpreting fishery-dependent bycatch (Abdul Razzaque et al., 2024a). An exploratory analysis of marine turtle records from the same programme used turtle-weighted kernel density estimation, H3 spatial aggregation and geodesic connections to investigate candidate seasonal Blue Corridors within Pakistan's EEZ (Abdul Razzaque et al., 2025), but explicitly flagged heterogeneous fishing effort, the absence of effort-standardized denominators, limited species identification and the lack of independent movement data as key limitations. The present study was designed to address these effort-standardization and inferential limitations rather than to treat the earlier spatial pattern as an independently validated corridor.

The distinction between fishery-interaction hotspots and biological movement corridors is fundamental. Fishery-interaction patterns arise from the intersection of animal occurrence, fishing activity and gear vulnerability, whereas ecological connectivity requires evidence that animals move among spatially connected areas, such as that provided by satellite telemetry, tagging or genetic analyses (Kot et al., 2023; Madden et al., 2025). Fishery-dependent data can identify where independent movement research may be valuable, but spatial clustering of interactions alone cannot establish a confirmed biological corridor. A further analytical challenge is the choice of exposure unit and spatial reference: turtle captures are comparatively rare events within a much larger population of fishing operations, and a gillnet operation has at least two recorded positions (SET and HAUL), while the exact entanglement location is generally unknown.

Using eight years (2012–2019) of Crew-based Observer Program (CBOP) data, this study developed a zero-inclusive, operation-standardized assessment of marine turtle–gillnet interactions in which one monitored fishing operation/set was the primary exposure unit. The specific objectives were to: (i) quantify interannual and fishing-phase variation in operation-standardized interactions; (ii) characterize taxonomic composition, body size and immediate release condition; (iii) assess vessel-level heterogeneity; (iv) quantify the sensitivity of fine-scale spatial assignment to coordinate representation and SET–HAUL reference choice; (v) identify formal IOTC 1×1 spatial hotspots using complementary burden and occurrence endpoints; (vi) evaluate the robustness of the resulting spatial pattern to year omission, fishing-method omission, resampling and an alternative effort definition; and (vii) integrate these lines of evidence into a spatial interaction-priority framework relevant to bycatch management and future Blue Corridor validation. The analytical framework explicitly separates fishery-dependent interaction evidence from biological connectivity, allowing long-term monitoring

data to identify immediate management priorities while providing a testable spatial hypothesis for future telemetry, tagging or genetic studies.

2. Materials and Methods

The analysis was implemented as a sequential, validated operation-primary workflow in which one monitored fishing operation/set was the primary exposure unit and zero-turtle operations were retained in all eligible rate and model populations. The workflow separated: (i) reconstruction of fishing operations and classification of turtle records; (ii) coordinate processing and SET/HAUL spatial-reference roles; (iii) operation-standardized interaction metrics, biological summaries and a secondary reported-net-km sensitivity; (iv) adjusted temporal models and descriptive vessel-level analyses; (v) formal IOTC 1 x 1 hotspot inference; (vi) integration of formal spatial evidence into an interaction-priority classification; (vii) immediate release-condition analysis; (viii) internal robustness and taxonomic support analyses; and (ix) final evidence synthesis and management/GIS translation. Later evidence-synthesis, mapping and scientific-communication stages inherited validated upstream estimates and classifications and did not create new statistical significance. Each component is summarized below; full analytical code and detailed diagnostic outputs are available from the corresponding author on request.

2.1 Study area, monitoring programme and analytical spatial framework

In this study, the fishery data were obtained from the WWF-Pakistan CBOP, which monitored tuna gillnet fishing operations in the northern Arabian Sea between 2012 and 2019. The programme was developed as an alternative to conventional onboard scientific observers, where vessel size, trip duration and onboard conditions limited feasibility; instead, trained vessel skippers and crew recorded minimum required standardized information on fishing operations, including fishing date, fishing method, gear configuration, SET and Haul positions,

catch, bycatch and interactions with non-target fauna, turtle counts, reported species identity, curved carapace length (CCL) where available, and immediate release condition using prescribed datasheets. marine-fauna interactions. These data are observations from monitored vessels and were not treated as a census of the national fleet. The design retained fishing operations both with and without recorded turtle interactions within the same analytical framework, so all subsequent analyses quantify turtle interactions relative to monitored fishing activity and are not estimates of turtle abundance or density.

The analytical domain extended from 60°E to 70°E and 18°N to 26°N. Fishing observations were assigned to three principal fishing phases (Early: August–October; Peak/Mid: November–January; Late: February–May), with June–July classified separately as the off-season/monsoon period and retained for descriptive purposes only and but were excluded from the principal three-phase and formal pooled August-May spatial analyses.

Formal spatial analyses were conducted on a regular 1°×1° latitude–longitude lattice using the IOTC Secretariat shapefile for all 1×1 regular grids within the IOTC area of competence (IOTC Secretariat, 2018); within the predefined analytical domain the complete lattice comprised 80 IOTC 1×1 cells. Pakistan's internal waters, territorial sea, contiguous zone and Exclusive Economic Zone were obtained from the Marine Regions Maritime Boundaries Geodatabase (Flanders Marine Institute, 2019a–d), high-seas context (Flanders Marine Institute, 2020), and the Extended Continental Shelf (Flanders Marine Institute, 2024). These marine-region boundaries were retained as geographic and jurisdictional reference layers only, did not redefine the IOTC 1×1 cells and were not used as alternative statistical units.

2.2 Fishing-operation reconstruction and turtle-record classification

Fishing operations were reconstructed from the source CBOP database. The source database contains repeated records associated with fishing operations, catches and fauna interactions.

Fishing operations were reconstructed so that repeated catch or interaction rows belonging to the same monitored operation did not create multiple units of fishing exposure. Each eligible operation contributed one unit to the primary denominator regardless of whether a turtle was recorded. Operations with no definite turtle capture were therefore retained as explicit zeros, preventing the analysis from being conditioned only on turtle-positive records.

Turtle records were standardized by recorded interaction status. Records reported as released alive (RA), released dead (RD), retained or discarded were treated as definite captures for the primary interaction numerator. Records with unresolved capture status were retained as an uncertain-capture sensitivity population but excluded from primary interaction, mortality, and hotspot numerators. Valid turtle sightings were preserved as a separate occurrence stream and were excluded from capture-rate, release-condition and formal hotspot inference. Turtle-positive operations, definite-capture bycatch-event rows, and TN_Count-derived turtle individuals were retained as distinct quantities throughout the workflow.

The primary rate population comprised eligible monitored fishing operations with an assignable analysis year in 2012-2019. Formal pooled spatial inference additionally required a valid SET position within the analysis domain and membership in the August-May primary fishing season. The exact source Fishing_Method field was retained; fishing methods were not pooled or replaced by broader gear categories merely to increase statistical support. A secondary vessel fishing-day exposure was defined as one unique anonymized Vessel_ID x normalized Fishing_Date combination and was used for descriptive summaries only, not as the primary denominator/ exposure unit.

2.3 Coordinate handling and spatial-reference sensitivity

The primary spatial stream used the original fishermen-reported degrees-and-decimal-minutes (DDM) coordinates. Raw DDM values were preserved for provenance, while valid coordinates

were converted to decimal degrees only for geospatial calculation and mapping. For a coordinate with degree component D and decimal-minute component M, the conversion was:

$$DD = D + \frac{M}{60}$$

SET and HAUL coordinates were assigned different analytical roles. SET was the canonical reference for operation-level rates, formal hotspot inference, priority classification and robustness analyses because it was available for both turtle-positive and zero-turtle fishing operations. Turtle-event biological and release summaries used HAUL as the preferred descriptive reference and SET only as a fallback when HAUL was unavailable under the validated event-linkage rules. Neither SET nor HAUL was interpreted as the exact entanglement location.

Two separate spatial-sensitivity questions were evaluated. First, the DDM-derived coordinates were compared with the historical pre-existing decimal-degree (Existing-DD) coordinate fields to quantify coordinate-source sensitivity. Second, where both SET and HAUL positions were available, endpoint-reference sensitivity was quantified using geodesic SET-HAUL displacement and whether the two endpoints fell in the same IOTC 1 x 1 cell. Great-circle displacement was calculated with the haversine equation (Sinnott, 1984), using the mean Earth radius $R = 6371.0088$ km consistent with the Geodetic Reference System 1980 (Moritz, 1980):

$$d = 2R \sin^{-1} \left(\sqrt{\sin^2 \left(\frac{\Delta\phi}{2} \right) + \cos\phi_1 \cos\phi_2 \sin^2 \left(\frac{\Delta\lambda}{2} \right)} \right)$$

where phi and lambda are latitude and longitude in radians. These comparisons were treated as spatial-assignment diagnostics and not as reconstructed fishing tracks or exact turtle-capture paths..

2.4 Operation-standardized interaction metrics, biological variables and alternative effort definition

For analytical group or spatial cell g , let O_g be the number of eligible monitored fishing operations, T_g the number of definite-capture turtle individuals, B_g the number of definite-capture bycatch-event rows, and P_g the number of turtle-positive operations. For operation i , turtle-positive occurrence was defined as $Z_i = 1$ when $T_i > 0$ and $Z_i = 0$ otherwise, so that $P_g = \sum Z_i$ within group g . The principal operation-standardized metrics were:

$$Z_i = \begin{cases} 1, & T_i > 0 \\ 0, & T_i = 0 \end{cases}$$

$$R_{T,g} = \frac{T_g}{O_g} \times 1000$$

$$R_{B,g} = \frac{B_g}{O_g} \times 1000$$

$$R_{P,g} = \frac{P_g}{O_g} \times 100$$

These quantities represent different estimands. $R_{T,g}$ measures turtle-individual interaction burden, $R_{B,g}$ describes event-row frequency, and $R_{P,g}$ describes the proportion of eligible fishing operations with at least one definite turtle capture. Turtle-individual burden and turtle-positive-operation occurrence were the two complementary primary endpoints for formal spatial inference; event rate was retained as supporting descriptive context.

Taxonomic labels were retained as reported in the source programme rather than externally corrected during analysis. CCL summaries used positive, quality-controlled measurements only. Missing lengths were not imputed; implausible measurements above 250 cm were excluded from the primary CCL stream, and rows in which the number of recorded CCL measurements exceeded the reported turtle count were excluded from primary CCL analysis. CCL was used as a measured body-size descriptor only and was not converted to maturity,

juvenile/adult or reproductive-status categories without independent species-specific validation.

Fishermen-reported net length was evaluated only as a secondary effort-definition sensitivity. For the subset of operations with valid positive reported net length L_g (km), the corresponding metrics were:

$$BPUE_g = \frac{T_g}{L_g} \times 1000$$

$$R_{PN.g} = \frac{P_g}{L_g} \times 1000$$

Reported net-km was never used to define primary operation eligibility, and missing or non-positive reported net length was not imputed. Nominal net-km-hours were retained only for compatibility or descriptive diagnostics and were not used for formal primary inference. Agreement between the operation-based and reported-net-km analyses was interpreted as internal denominator robustness, not as independent validation.

2.5 Temporal models and vessel-level descriptive analysis

Annual and fishing-phase interaction summaries were first calculated using the zero-inclusive operation denominator. Adjusted temporal associations were then evaluated on the primary August-May operation population using two complementary generalized linear models (McCullagh & Nelder, 1989), with one row per fishing operation and no effort offset: a binomial logistic model for turtle-positive occurrence and a log-link count model for turtle individuals:

$$\text{logit}[\text{Pr}(Z_i = 1)] = \gamma_0 + \sum_k \gamma_k X_{ik}$$

$$\log[E(T_i)] = \beta_0 + \sum_k \beta_k X_{ik}$$

Candidate contextual factors were analysis year, fishing phase and the exact source Fishing_Method. A categorical factor was retained only when every observed level had at least 30 eligible operations, three turtle-positive operations and three turtle individuals; sparse categories were not combined solely to force model fitting. Vessel dependence was addressed using covariance clustered by anonymized Vessel_ID when at least 20 vessel clusters were available. The count model was fitted as a robust Poisson mean model, with a negative-binomial-2 sensitivity when overdispersion warranted it (Hilbe, 2011). Categorical year was the principal temporal specification, and a continuous-year formulation was retained as a named sensitivity for the overall temporal direction. Benjamini-Hochberg false-discovery-rate adjustment (Benjamini & Hochberg, 1995) was applied to the relevant model-coefficient families, and adjusted results are reported as odds ratios or count-rate ratios with 95% confidence intervals. These contextual temporal models did not generate or redefine spatial hotspot significance.

Vessel-level analysis was descriptive. Vessel-specific operation-standardized rates were displayed as supported only for anonymized vessels with at least 30 monitored operations and at least three turtle-positive operations; monitoring histories spanning at least three years were separately identified as multi-year coverage. No vessel-specific rate was interpreted as an intrinsic or causal vessel-risk effect because vessels differed in monitoring duration, fishing phase, method and spatial coverage. Sampling and interaction concentration were summarized using top-vessel shares and the Herfindahl-Hirschman Index (HHI; Herfindahl, 1950; Hirschman, 1964). For vessel v with contribution x_v and share s_v :

$$s_v = \frac{x_v}{\sum_k x_k}, \quad \text{HHI} = \sum_v s_v^2$$

HHI was calculated separately for monitored operations, turtle-positive operations and turtle individuals. Vessel fishing-day summaries were retained as secondary descriptive context and were not substituted for the operation-level denominator.

2.6 Formal IOTC 1 x 1 spatial hotspot inference

Formal hotspot inference was conducted on SET-referenced operations at the IOTC 1 x 1 scale. A cell was support-qualified when it contained at least 10 eligible monitored fishing operations and had at least one similarly support-qualified queen-contiguous neighbour (sharing an edge or corner). At least four support-qualified cells were required for a spatial subset to be formally testable. Year-, phase- and Fishing_Method-specific subsets additionally required at least 100 eligible operations, three turtle-positive operations and three turtle individuals before local inference was attempted. A mathematically or support-limited subset was labelled not formally testable and was not interpreted as evidence of no hotspot.

Local clustering was evaluated using the local Getis-Ord G_i^* statistic (Getis & Ord, 1992; Ord & Getis, 1995), with queen-contiguity weights and the focal cell included in its own neighbourhood. For n formally eligible cells, cell-level interaction metric x_j , global mean $\bar{X}$, global standard-deviation term S and spatial weight w_{ij} :

$$G_i^* = \frac{\sum_j w_{ij} x_j - \bar{X} \sum_j w_{ij}}{S \sqrt{\frac{n \sum_j w_{ij}^2 - (\sum_j w_{ij})^2}{n - 1}}}$$

$$\bar{X} = \frac{1}{n} \sum_j x_j, \quad S = \sqrt{\frac{1}{n} \sum_j x_j^2 - \bar{X}^2}$$

Rather than applying an unconditional spatial randomization, the null distribution was generated at the fishing-operation level from support-qualified observation-process models. Candidate conditioning factors were analysis year, fishing phase, exact Fishing_Method and

anonymized Vessel_ID. A factor was retained only when every observed level satisfied at least 30 operations, three turtle-positive operations and three turtle individuals. No factor category was pooled solely to meet this gate.

For turtle-individual burden, the conditional null used an operation-level Poisson count model without an effort offset, with an NB2 simulation variance when the fitted overdispersion parameter exceeded the predefined threshold (McCullagh & Nelder, 1989; Hilbe, 2011). For turtle-positive occurrence, the conditional null used an operation-level Bernoulli/logistic model, also without an effort offset:

$$Y_i \sim \text{Poisson}(\mu_i) \text{ or } \text{NB2}(\mu_i, \alpha), \quad \log(\mu_i) = \beta_0 + \sum_k \beta_k X_{ik}$$

$$\text{Var}(Y_i) = \mu_i + \alpha \mu_i^2, \quad \text{NB2 simulation used when } \alpha > 0.05$$

$$Z_i \sim \text{Bernoulli}(p_i), \quad \text{logit}(p_i) = \gamma_0 + \sum_k \gamma_k X_{ik}$$

For each formally testable subset and endpoint, 1,999 conditional Monte Carlo replicates were simulated at the operation level, re-aggregated to the analytical IOTC cells, and the local Gi* statistic recomputed. The two-sided Monte Carlo probability used the conventional +1 correction so that a randomly simulated reference distribution could not produce a zero p-value (Phipson & Smyth, 2010):

$$p_i = \frac{1 + \sum_{r=1}^R I(|G_{i,r}^*| \geq |G_{i,\text{obs}}^*|)}{R + 1}, \quad R = 1999$$

Within each formally tested spatial subset and endpoint, Monte Carlo p-values were adjusted using the Benjamini-Hochberg false-discovery-rate procedure (Benjamini & Hochberg, 1995). A formal high-interaction hotspot required both a positive local statistic and a two-sided FDR-adjusted q-value ≤ 0.05 :

$$G_i^* > 0 \quad \text{and} \quad q_i \leq 0.05$$

The primary formal endpoints were (1) turtle individuals per 1,000 monitored fishing operations and (2) turtle-positive-operation percentage. Because G_i^* is a neighbourhood statistic, a formal hotspot identifies a cell embedded in a local cluster of elevated interaction values and does not imply that most turtle captures occurred inside the focal cell.

A separate reported-net-km formal sensitivity was conducted on its own valid positive-net-length population. The count sensitivity used a log-link count model with log(reported net-km) as an offset, while the turtle-positive-operation sensitivity used a complementary-log-log formulation with the same exposure offset before conditional spatial simulation. These net-km results could corroborate a primary operation-based formal hotspot but could not create primary formal significance in a cell that was not a primary hotspot.

2.7 Integrated interaction-priority classification

Formal spatial significance was translated into a conservative interaction-priority hierarchy without recalculating G_i^* , p-values or q-values. A cell was first classified as a primary formal hotspot when either of the two primary endpoints met the criterion in Section 2.6. Among primary formal cells, Tier 1 required at least one additional corroborating dimension: (i) formal confirmation by both primary endpoints; (ii) endpoint-matched formal recurrence in at least two supported year-, phase- or Fishing_Method-specific subsets; or (iii) endpoint-matched formal concordance with the secondary reported-net-km sensitivity. Other primary formal hotspot cells were classified as Tier 2.

Cells that were formally tested but were not primary formal hotspots could be retained as contextual monitoring evidence only when at least one pre-specified non-formal criterion was met: operation-standardized turtle burden at or above the 75th percentile among formally tested cells, a model-based turtle-count observed/expected ratio ≥ 1.5 , or a turtle-positive-operation

observed/expected ratio ≥ 1.5 . These cells were explicitly labelled context only and were not promoted to formal hotspot status. Formally tested cells without either formal or contextual evidence were classified as having no primary formal hotspot evidence, whereas cells that failed the formal support gate were classified as having insufficient formal spatial support.

Connected interaction-priority areas were defined from queen-contiguous Tier 1 or Tier 2 cells. The pipeline additionally allowed an internally supported connected component to be flagged as a candidate Blue Corridor segment only when it contained at least two connected formal-priority cells and at least two Tier 1 cells. This designation was treated solely as a fishery-interaction hypothesis: it did not establish turtle abundance, habitat preference, exact entanglement position or biological movement connectivity, all of which would require independent telemetry, tagging, genetic or other movement/connectivity evidence

2.8 Immediate release-condition analysis

Immediate release condition was analysed separately from interaction occurrence and spatial hotspot inference. The primary release population comprised definite-capture, single-turtle event rows with determined RA or RD status. This restriction avoided treating a single row-level status recorded for a multi-turtle event as multiple independent turtle fates. Determined multi-turtle rows and TN_Count-weighted totals were retained as descriptive sensitivities only. Retained, discarded and unresolved-status records did not enter the RA/RD denominator.

For N_{RA} eligible single-turtle events released alive and N_{RD} released dead, immediate released-dead proportion was:

$$M_{RD} = \frac{N_{RD}}{N_{RA} + N_{RD}}$$

Wilson score 95% confidence intervals were used for release proportions (Wilson, 1927). Where data support permitted, binomial logistic models (McCullagh & Nelder, 1989) evaluated

temporal and operational associations with RD versus RA without an effort offset. Candidate categorical factors were support-gated and exact source categories were retained rather than synthetically pooled; vessel-clustered covariance was used when supported by the number of vessel clusters. Because sparse or zero-RD levels can make categorical terms non-estimable, unsupported factors were not forced into the model. A continuous-year model was retained as a named sensitivity to the overall temporal direction.

CCL-release association was evaluated only in the measured, linked single-turtle RA/RD subsample. CCL was centred on the sample mean and expressed per 10-cm increment:

$$CCL_{10,i} = \frac{CCL_i - \overline{CCL}}{10}, \quad \text{logit}(p_i) = \beta_0 + \beta_1 CCL_{10,i}, \quad OR_{10\text{cm}} = e^{\beta_1}$$

Release-condition maps and marine-region summaries were descriptive only and used the HAUL-primary/SET-fallback event reference. No release-outcome map generated a local hotspot, priority or corridor criterion. RD/(RA+RD) represents immediate condition at release only and was not interpreted as delayed post-release mortality or total fishing mortality.

2.9 Internal robustness, taxonomic disaggregation and final evidence synthesis

Internal spatial robustness was evaluated only after primary formal hotspot status had been established. The checks comprised leave-one-year-out (LOYO) formal re-analysis, sequential omission of each exact Fishing_Method, 1,000 whole-operation bootstrap replicates, 1,000 vessel-block bootstrap replicates where vessel support was adequate, and endpoint-matched concordance with the secondary reported-net-km formal sensitivity. Bootstrap resampling followed the general non-parametric resampling framework of Efron and Tibshirani (1993). LOYO and method-omission recurrence were calculated only across scenarios in which the cell remained formally testable; non-testable scenarios were excluded from the recurrence denominator rather than counted as failures:

$$R_{\text{LOYO},g} = 100 \frac{H_{\text{LOYO},g}}{N_{\text{testable,LOYO},g}}, \quad R_{\text{method},g} = 100 \frac{H_{\text{method},g}}{N_{\text{testable,method},g}}$$

Whole-operation bootstrap replicates resampled complete fishing operations within Analysis_Year x Fishing_Phase strata and quantified recurrence of the high-interaction rate surface; they did not generate new Gi*/FDR significance. Vessel-block bootstrap replicates resampled anonymized vessel blocks and quantified dependence on the monitored vessel sample rather than fleet-wide vessel effects. Agreement between each resampled cell-level interaction surface and the corresponding baseline surface was additionally summarized using Spearman rank correlation (Spearman, 1904). Reported-net-km concordance remained a separate effort-definition robustness dimension.

For baseline primary formal hotspot cells, internal-stability classes followed pre-specified thresholds. Adequate deletion-test coverage required at least 75% of possible testable scenarios. High internal stability required all available LOYO, method-omission and operation-bootstrap recurrence metrics to be at least 75%, vessel-bootstrap recurrence to be at least 60% when available, and concordance with the alternative reported-net-km effort definition. Moderate internal stability required the corresponding recurrence metrics to be at least 50% and vessel-bootstrap recurrence to be at least 40% when available. Baseline formal cells not meeting these thresholds were classified as low internal stability, while inadequate test coverage yielded insufficient internal-stability evidence. Cells that were not baseline primary formal hotspots were not promoted by robustness analysis.

When two hotspot sets A and B were compared, spatial overlap was summarized using the Jaccard similarity index (Jaccard, 1912):

$$J(A, B) = \frac{|A \cap B|}{|A \cup B|}, \quad 0 \leq J(A, B) \leq 1$$

Taxonomic disaggregation used exact reported Species and Taxon_Group labels and the same complete zero-inclusive August-May SET-operation denominator for each category; fishing effort was not partitioned among species. A reported category was eligible for formal category-specific spatial testing only when it contained at least 20 category-positive operations, 20 turtle individuals and four positive IOTC 1 x 1 cells. Categories below this gate were labelled data deficient for formal spatial inference, not as having no hotspot or no risk. Support-qualified categories were analysed with the same conditional operation-level G_i^*/BH -FDR framework used for the pooled analysis. Where an exact all-turtle aggregate category was analytically identical to the pooled population, the authoritative pooled formal inference was inherited rather than treated as an independent replication.

Final evidence synthesis was deterministic and created no new formal significance. Primary formal hotspot status was inherited only from the formal spatial analysis; Tier 1/Tier 2 status from the integrated priority stage; internal stability from the robustness stage; exact reported-species/taxon results as internal taxonomic corroboration or context; and immediate release condition as a separate capture-consequence endpoint. Non-formal cells could therefore not be promoted to a formal evidence class by robustness, species overlap, reported-net-km concordance or contextual model evidence. Internal corroboration was interpreted as consistency within the same fishery-dependent monitoring programme, not as external validation or a probability that a biological corridor is true.

The final management/GIS stage translated the evidence classes into reporting and management labels without recalculating hotspot statistics, priority tiers, robustness, species evidence or release outcomes. Publication figures and supplementary scientific-communication maps were generated from these validated outputs using read-only visualization routines; they did not alter analytical populations, denominators, p-values, q-

values, priority classes or evidence classes. Analyses were implemented in Python using version-controlled stage handoffs and scientific reconciliation checks, with pandas, NumPy, GeoPandas, SciPy, statsmodels and Matplotlib used for data processing, statistical analysis, geospatial operations and visualization.

3. Results

Results are presented in the same sequence as the study objectives: dataset coverage the temporal patterns, biological composition and body size, immediate release condition, vessel-level heterogeneity, sensitivity of fine-scale spatial assignment, formal spatial hotspot inference, the integrated spatial interaction-priority area; and internal robustness of that spatial evidence. Throughout operation-standardised metrics use the zero-inclusive primary operation denominator described in Section 2.4 unless a secondary reported-net-km sensitivity is explicitly identified.

3.1 Analytical coverage and dataset

The source database contained 108,041 records consisting of the 32,186 monitoring fishing operations from 2012-2019, included 979 candidate marine turtle records, 867 records (955 turtle individuals) met the criteria for definite capture, 49 records were retained as an uncertain-capture sensitivity, and seven valid sightings were retained as a separate occurrence stream (Table 1).

Reconstruction of fishing activity produced 32,213 monitored fishing operations, of which 32,186 fell within 2012–2019, 11 were dated in 2020 and 16 lacked an assignable analysis year. The primary rate-model population comprised 30,195 eligible operations (93.7% of the reconstructed backbone), of which 845 (2.8%) were turtle-positive and 29,350 (97.2%) recorded no definite turtle capture — confirming that the primary population was strongly zero-

inclusive, as required for unbiased rate estimation. Within the study period, monitoring corresponded to 29,398 unique vessel fishing days, retained as a descriptive secondary exposure measure rather than the primary denominator, since a single vessel fishing day could contain more than one monitored operation. Linkage between biological capture records and the operation denominator was nearly complete: of 867 definite-capture event records, 864 (99.7%), accounting for 952 of 955 turtle individuals (99.7%), were uniquely linked to a monitored fishing operation, with the remaining three individuals retained in biological summaries but excluded from operation-standardised rate analyses. Using the primary DDM coordinates, 28,694 operations (95.0% of the rate population) were eligible for SET-referenced spatial analysis, and 28,621 operations within the three principal August–May fishing phases formed the primary formal spatial-analysis population used for pooled hotspot inference (Table 1, Figure 1).

Analytical component	n	% / role
Source database records	108,041	—
Marine turtle candidate records	979	—
Definite-capture event records / individuals	867 / 955	—
Uncertain-capture records	49	Sensitivity only
Valid turtle sightings	7	Excluded from rate analyses
Monitored fishing operations (backbone)	32,213	—
Operations dated 2012–2019	32,186	—
Primary rate-model population	30,195	93.7% of backbone
of which turtle-positive	845	2.8%
of which zero-turtle	29,350	97.2%
DDM SET-spatial eligible operations	28,694	95.0% of rate population
Primary formal spatial (Aug.–May) population	28,621	Primary hotspot-analysis population
Unique vessel fishing days, 2012–2019	29,398	Descriptive only

Table 1. Dataset screening and analytical populations used in the marine turtle–tuna gillnet interaction analyses. One monitored fishing operation/set, rather than one fishing day, was the primary analytical exposure unit.

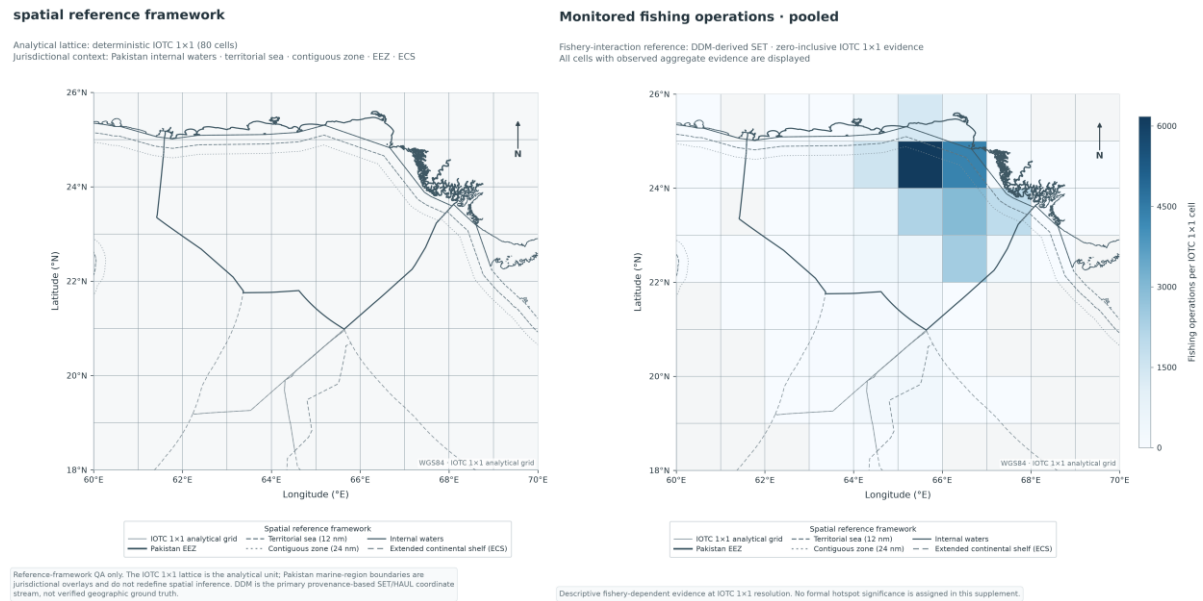


Figure 1. Study area and spatial coverage of the monitored tuna gillnet fishery used in the marine turtle interaction analyses. (A) IOTC 1×1 analytical lattice with Pakistan's internal waters, territorial sea, contiguous zone, Exclusive Economic Zone and Extended Continental Shelf shown as geographic and jurisdictional context. (B) Spatial distribution of SET-referenced fishing operations eligible for the zero-inclusive spatial analysis. Spatial reference sources: IOTC Secretariat (2018) for the IOTC 1×1 grid; Flanders Marine Institute (2019a–d, 2020, 2024) for the maritime-boundary reference layers.

3.2 Temporal patterns

Operation-standardised turtle-individual interaction rates were highest in 2013 (251.8 per 1,000 operations), 2014 (208.9) and 2012 (191.5), declined to 61.9 in 2015 and 20.6 in 2016, reached a minimum of 10.3 in 2017, and increased modestly to 15.0 in 2018 and 16.6 in 2019; turtle-positive operations showed the same pattern, falling from 14.9–20.8% of operations (2012–2014) to 1.0–1.9% (2016–2019) (Figure 2). This decline remained after simultaneous adjustment for fishing phase in vessel-clustered models: relative to 2012, adjusted turtle-count ratios and turtle-positive odds ratios were significantly below 1.0 from 2015/2016 onward and remained strongly supported through 2019 after FDR correction (Table 2). A continuous-year sensitivity model confirmed the overall decline (turtle-positive OR per year = 0.526, 95% CI: 0.422–0.657; count ratio per year = 0.540, 95% CI: 0.447–0.652; both $P < 0.001$), though the modest post-2017 increase indicates the trajectory was not strictly monotonic. Descriptive rates were highest in the Peak/Mid phase, but pooled fishing-phase differences (Table 2B) were not

statistically supported once analysis year was taken into account. The secondary net-km sensitivity reproduced the same broad temporal decline.

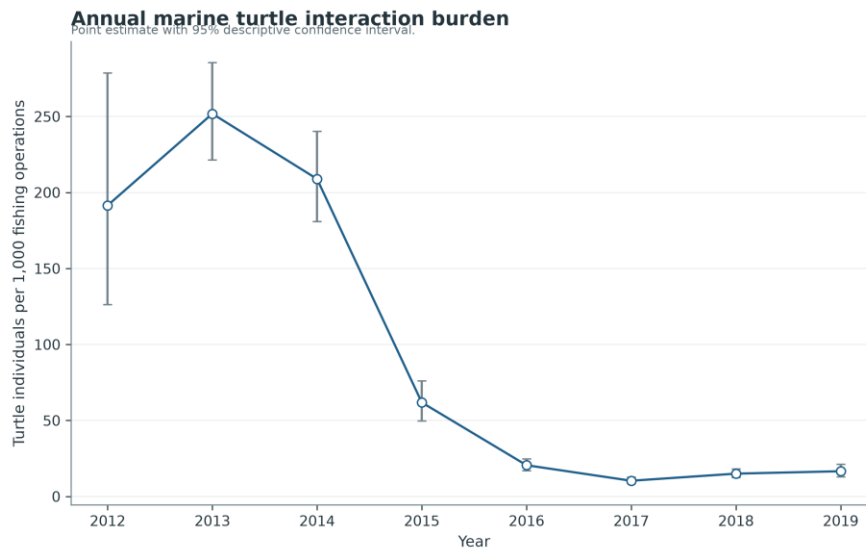


Figure 2. Annual marine turtle interaction rate (turtle individuals per 1,000 eligible operations) in the monitored fishery, 2012–2019. Adjusted temporal effects accounting simultaneously for year and fishing phase are reported in Table 2.

Analysis year	Count ratio*	q	Turtle-positive OR*	q
2012	1.000 (ref.)	—	1.000 (ref.)	—
2013	1.299	0.631	1.423	0.542
2014	1.090	0.847	1.243	0.760
2015	0.335	0.015	0.356	0.059
2016	0.108	<0.001	0.107	<0.001
2017	0.054	<0.001	0.056	<0.001
2018	0.078	<0.001	0.073	<0.001
2019	0.087	<0.001	0.088	<0.001

*Relative to the fishing-phase-adjusted GLM null; vessel-clustered covariance.

Table 2. Adjusted year effects on operation-standardised marine turtle interactions (August–May operation population, $n = 30,121$). Bold significance corresponds to $q < 0.05$. Fishing-phase effects (Peak/Mid vs. Early: count ratio = 1.094, $q = 0.727$, OR = 1.041, $q = 0.854$; Late vs. Early: count ratio = 1.130, $q = 0.727$, OR = 1.158, $q = 0.692$) were not statistically supported after adjustment for year.

3.3 Biological composition and body size

Of 955 definite-capture turtle individuals, 936 (98.0%) were reported under the aggregate category Turtle spp.; only 19 individuals were assigned to named species (10 olive ridley, 3

loggerhead, 3 hawksbill, 2 green, 1 leatherback). No named species satisfied the pre-specified support requirements (≥ 20 turtle-positive operations, ≥ 20 individuals, occurrence in ≥ 4 IOTC 1×1 cells) for formal species-specific spatial inference; the absence of species-specific hotspot results therefore reflects insufficient analytical support rather than low interaction risk or biological absence. Quality-controlled CCL measurements ($n = 464$, from 427 records/417 operations) had a mean of 56.3 cm (SD 20.0), median 58.5 cm (IQR 41.0–72.0 cm, range 4–112 cm); mean CCL differed descriptively among fishing phases (Early 52.0 cm, Peak/Mid 58.1 cm, Late 56.9 cm) but species-level size comparisons were not informative given the dominance of unidentified records.

3.4 Immediate release condition

Among 782 determined single-turtle capture events, 751 were released alive and 31 released dead, an immediate RD proportion of 3.96% (Wilson 95% CI: 2.81–5.57%). This reflects condition at release only and does not capture delayed or post-release mortality. Estimates were similar when multi-turtle event rows were included (3.81%, 95% CI: 2.72–5.30%) or weighted by turtle count (3.66%), and stable under leave-one-year-out exclusion (range 2.97–4.57%). RD proportions by fishing phase (Early 4.84%, Peak/Mid 5.88%, Late 2.05%) were not statistically different after adjustment (Peak/Mid OR = 1.23, 95% CI: 0.63–2.38, $P = 0.540$; Late OR = 0.41, 95% CI: 0.08–2.21, $P = 0.301$). Annual RD was highest early in the programme (30.4% in 2012, declining to 3.2–7.4% by 2013–2015, with zero events in 2016, 2017 and 2019); a year-only sensitivity model (not adjusted for phase) indicated a declining trend (OR per year = 0.507, 95% CI: 0.308–0.833, $P = 0.007$). Measured body size was not associated with immediate release condition (OR = 0.96 per 10-cm CCL increase, 95% CI: 0.70–1.31, $P = 0.789$).

3.5 Vessel-level heterogeneity

The primary population included 142 anonymised vessels. Monitoring effort was comparatively dispersed (the top 5 and 10 vessels accounted for 17.0% and 27.0% of eligible operations, respectively), but recorded turtle interactions were far more concentrated. The top 5 vessels accounted for 56.5% of linked turtle individuals and 55.0% of turtle-positive operations from only 14.0% of eligible operations, and the top 10 vessels accounted for 70.5% and 69.3% from 19.2% of operations. Herfindahl–Hirschman concentration indices were 0.0149 for fishing operations versus 0.0924 (turtle-positive operations) and 0.1000 (turtle individuals). Among 23 vessels satisfying rate-support and longitudinal-coverage criteria, interaction rates ranged from 4.1 to 400.3 individuals per 1,000 operations (median 27.8). Because higher-rate vessels were also monitored predominantly in earlier, higher-interaction years, vessel-level differences were interpreted as descriptive heterogeneity reflecting combinations of year, location, method and operational practice rather than intrinsic vessel-specific risk; the vessel-block bootstrap (Section 3.9) tested whether the spatial pattern was robust to this dependence structure.

3.6 Sensitivity of spatial assignment to coordinate and endpoint reference

Fine-scale spatial assignment was sensitive to both coordinate provenance and operational endpoint. Comparing historical decimal-degree coordinates with the primary DDM stream altered IOTC 1×1 cell assignment for 6.6% of comparable operations and 14.9% of comparable capture events. Among operations with a complete SET–HAUL pair (94.1% of 2012–2019 operations), median SET–HAUL displacement was 10.04 km (IQR 6.81–14.28 km, 95th percentile 86.34 km), and 13.1% of comparable operations (14.0% of turtle-positive operations) changed IOTC 1×1 cell assignment depending on which endpoint was used. These results supported SET as the standardized spatial reference for zero-inclusive operation-level analyses, since it can be applied consistently to both turtle-positive and zero-turtle operations; neither SET nor HAUL should be interpreted as the exact turtle-entanglement location, and

hotspot outputs should be read as SET-referenced fishery-interaction patterns rather than maps of capture locations.

3.7 Spatial hotspots of marine turtle–gillnet interactions

Formal pooled spatial inference used 28,621 SET-referenced operations from the three principal fishing phases (805 turtle-positive operations, 822 linked capture events, 907 turtle individuals). Of the 80-cell IOTC 1×1 lattice, 35 cells met the formal support requirements. Four contiguous cells were identified as formal hotspots for both turtle-individual burden and turtle-positive-operation occurrence (Table 3, Figure 3): IOTC1_62E_21N, IOTC1_62E_22N, IOTC1_63E_21N and IOTC1_63E_22N. Within these cells, turtle-individual rates ranged from 77.8 to 200.0 per 1,000 operations and 7.8–20.0% of operations were turtle-positive; all four cells had positive G_i^* statistics and remained significant after FDR correction (burden $q = 0.0058$ – 0.0088 ; occurrence $q \approx 0.0044$). Notably, the four cells together contained only 20 of the 907 turtle individuals in the spatial population — because G_i^* is a neighborhood statistic, formal hotspot status reflects statistically elevated local clustering rather than the majority of recorded captures. All four cells were reproduced under the secondary net-km sensitivity for turtle-positive occurrence (Jaccard = 1.00) and for burden (Jaccard = 0.80, with the net-km analysis also identifying one additional burden-only cell); burden rates under the two effort frameworks were very strongly correlated across 55 comparable cells (Spearman $\rho = 0.997$, $P = 2.4 \times 10^{-60}$). Phase- and year-specific disaggregation showed weaker recurrence (no cell was a formal hotspot in more than one of the three phase-specific analyses, and only one cell/year combination — IOTC1_65E_22N in 2016 — was a formal annual hotspot), indicating that the pooled configuration represents an integrated multi-year pattern rather than a fixed year-round hotspot. Only the aggregate Turtle spp. category had sufficient support for formal spatial testing and reproduced the same four cells; no named species had sufficient support for species-specific hotspot inference.

IOTC 1×1 cell	Operations	Turtles	Rate /1,000 ops	Positive ops (%)	Burden q	Occurrence q
IOTC1_62E_21N	25	5	200.0	20.0	0.0088	0.0044
IOTC1_62E_22N	22	3	136.4	13.6	0.0058	0.0044
IOTC1_63E_21N	59	5	84.7	8.5	0.0058	0.0044
IOTC1_63E_22N	90	7	77.8	7.8	0.0058	0.0044

Table 3. Formal IOTC 1×1 marine turtle–gillnet interaction hotspots (positive local Getis–Ord G_i^* , two-sided Benjamini–Hochberg $q \leq 0.05$; pooled August–May analysis, conditional null adjusted for year and fishing phase). All four cells were classified as High internal evidence after robustness synthesis (Section 3.9).

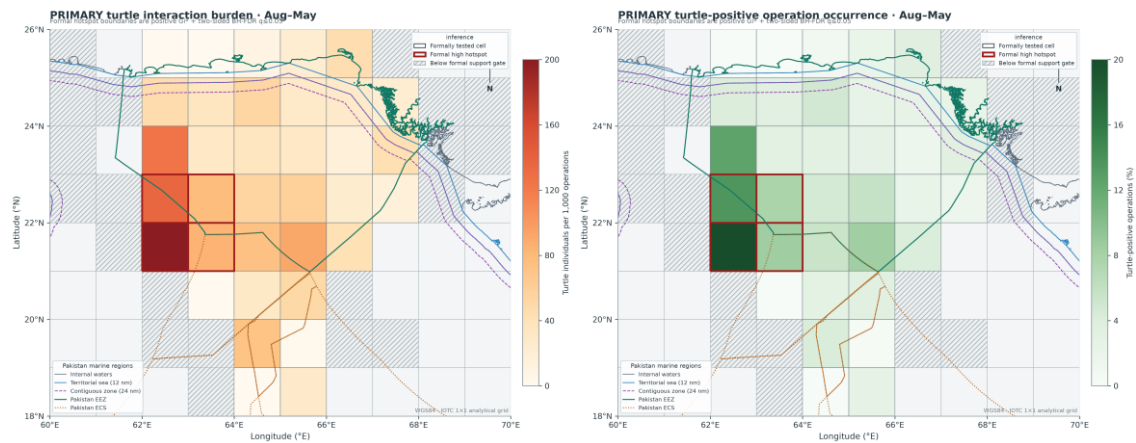


Figure 3. Formal spatial distribution of marine turtle–gillnet interaction rates across the IOTC 1×1 lattice, pooled August–May analysis. (A) Turtle individuals per 1,000 operations and formal burden hotspots. (B) Turtle-positive-operation percentage and formal occurrence hotspots.

3.8 Integrated spatial interaction-priority area

Integration of formal hotspot status, robustness and taxonomic context across the 80-cell lattice classified 4 cells as High internal evidence, 12 as Context only (no primary formal hotspot), 19 as formally tested with no formal hotspot evidence, and 45 as having insufficient formal spatial support. The 45 insufficient-support cells should not be interpreted as low-risk, because formal inference was not adequately supported in those areas (Figure 4A).

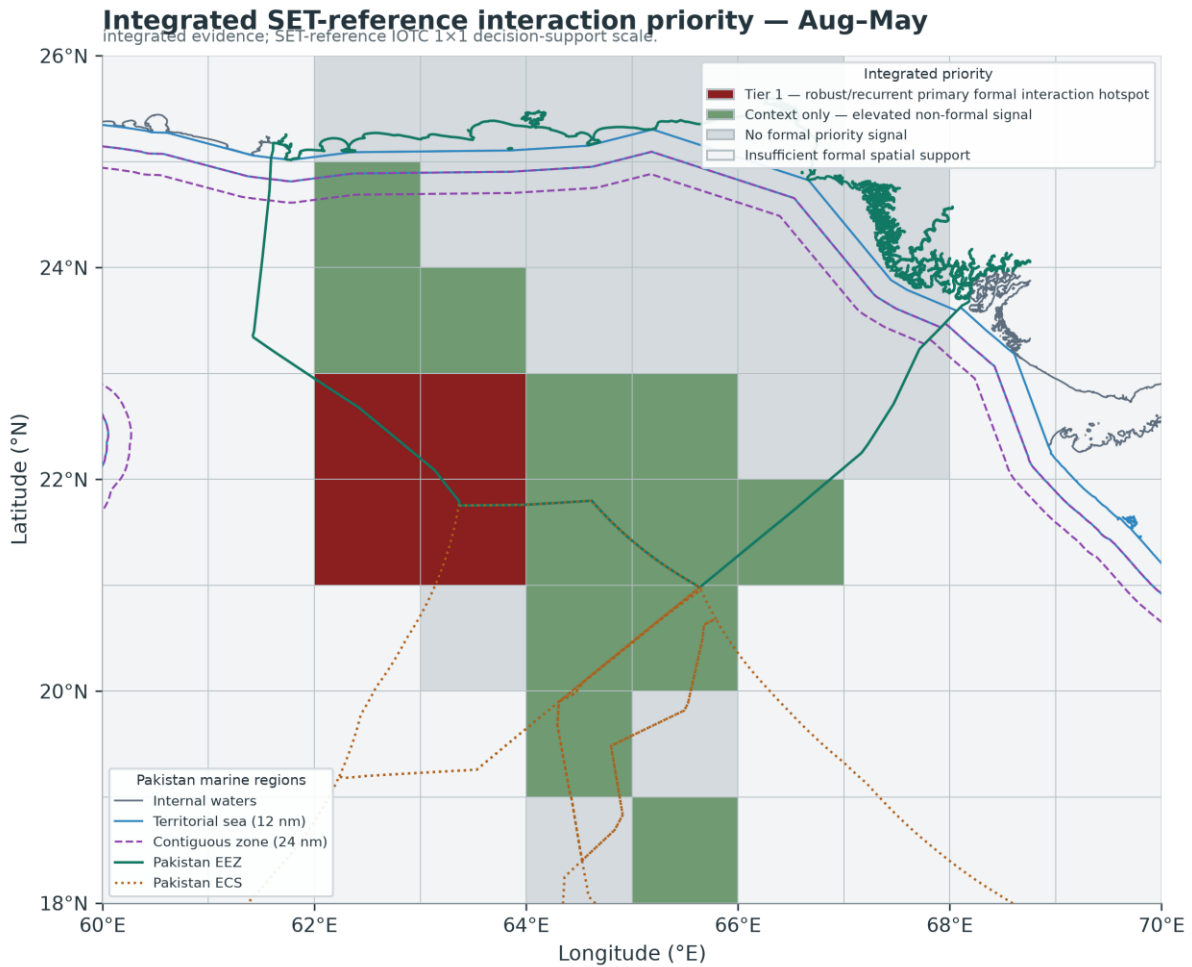


Figure 4A. Integrated spatial priority classification for marine turtle–gillnet interactions across the IOTC 1×1 lattice, distinguishing High internal evidence, Context only, formally tested/no hotspot, and insufficient-support cells.

3.9 Internal robustness of the interaction-priority area

The four Tier 1 cells were consistently supported across all internal robustness checks (Table 4). Under leave-one-year-out analysis, each cell remained formally testable in all eight annual-deletion scenarios and was reclassified as a hotspot in seven of eight (87.5% recurrence). Three cells remained hotspots in 100% of fishing-method-omission scenarios in which they were testable, and the fourth in 87.5%. Across 1,000 whole-operation bootstrap replicates, high-interaction recurrence ranged from 88.9–98.4% (median Spearman correlation with the baseline surface: 0.896 burden, 0.894 occurrence); across 1,000 vessel-block bootstrap replicates, recurrence ranged from 63.9–95.5% (median correlation 0.926 and 0.925), the wider range reflecting the vessel concentration described in Section 3.5. All four cells were also

concordant with the net-km sensitivity, and together these results met the pre-specified criteria for High internal stability for all four cells. These robustness analyses strengthen confidence that the four-cell pattern was not determined by a single year, fishing method, resampled subset or effort definition; however, because all analyses derive from the same fishery-dependent monitoring programme, they represent internal analytical stability rather than independent ecological validation and do not demonstrate turtle movement, habitat preference or biological connectivity among the four cells.

IOTC 1×1 cell	LOYO recurrence	Method-omission recurrence*	Operation-bootstrap	Vessel-bootstrap	Net-km concordant	Stability class
IOTC1_62E_21N	87.5%	100.0%	98.4%	95.5%	Yes	High
IOTC1_62E_22N	87.5%	100.0%	92.1%	63.9%	Yes	High
IOTC1_63E_21N	87.5%	100.0%	88.9%	87.6%	Yes	High
<i>IOTC1_63E_22N</i>	87.5%	87.5%	91.7%	91.1%	<i>Yes</i>	<i>High</i>

*Calculated among scenarios in which the cell remained formally testable (7 of 8 method-omission scenarios for the first three cells; 8 of 8 for IOTC1_63E_22N).

Table 4. Internal robustness of the four Tier 1 marine turtle–gillnet interaction-priority cells. LOYO = leave-one-year-out

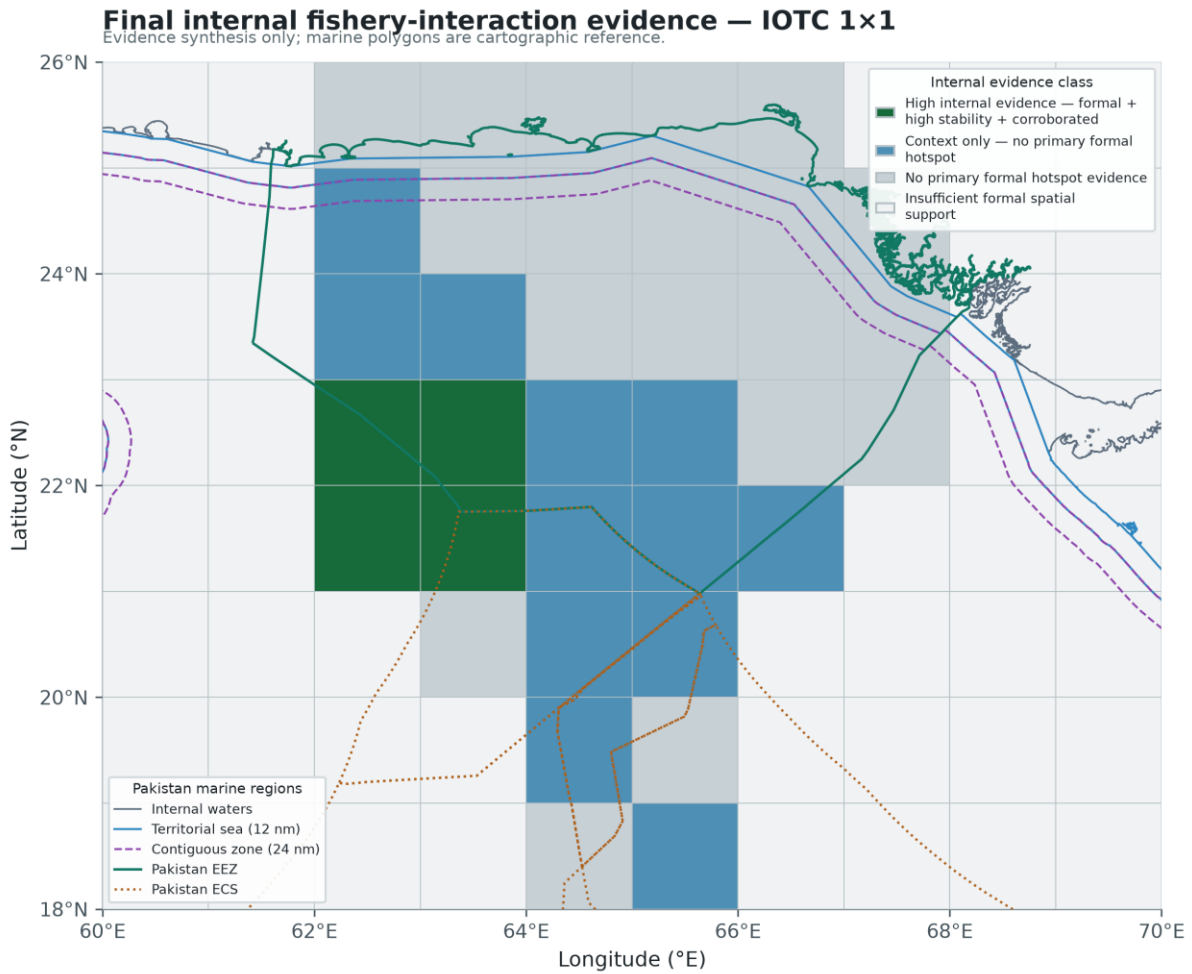


Figure 4B. Final internal evidence classification integrating formal hotspot status, robustness and effort-definition concordance across the IOTC 1×1 lattice. Insufficient-support cells should not be interpreted as low-risk.

4. Discussion

4.1 Overview and significance of findings

This study provides an operation-standardized assessment of marine turtle interactions with Pakistan's tuna gillnet fishery over 2012–2019. By reconstructing a zero-inclusive fishing-operation denominator, the analysis moves beyond descriptions based solely on recorded encounters and evaluates interactions relative to the fishing activity in which they could have occurred. Three findings stand out: a marked temporal decline in operation-standardised interactions that persisted after adjustment for fishing phase and under an alternative effort definition; a small, connected group of IOTC 1×1 cells with elevated turtle-individual burden

and turtle-positive-operation occurrence; and comparative stability of that spatial pattern across leave-one-year-out, fishing-method-omission, resampling and effort-definition sensitivities. The value of these results lies in convergence across multiple analytical lines of evidence rather than in any single hotspot map, providing a stronger basis for spatially targeted monitoring and mitigation than an encounter-only analysis. The framework deliberately preserves the distinction between fishery-interaction priority and biological ecological importance and represents an analytical progression from the earlier exploratory Blue Corridors assessment (Abdul Razzaque et al., 2025) toward a formally tested, operation-standardized interaction framework; because both analyses derive from the same broader monitoring programme, they should not be treated as independent validation of one another.

4.2 Interpreting the temporal decline in turtle interactions

The pronounced decline in operation-standardized interactions is one of the clearest findings of the study, and it persisted after adjustment for fishing phase, whereas apparent differences among phases were not supported once year was accounted for, indicating that broad temporal change was more influential than a consistently expressed seasonal effect. The mechanisms underlying this decline cannot be determined from the present observational analysis. Changes in recorded interaction rates could arise from shifts in fishing location, fleet composition, fishing practices, environmental conditions, turtle availability, reporting behavior, or combinations of these factors, and should not be attributed to any single management intervention or gear change without a dedicated analysis designed to test that mechanism. This caution is consistent with experience elsewhere in the same monitoring programme, where a spatiotemporal analysis of dolphin bycatch likewise found complex temporal, spatial and operational structure and emphasized the difficulty of isolating a single driver of change (Abdul Razzaque et al., 2024a). Critically, the distinction between declining interaction rates and declining turtle abundance is important. The reduction in operation-standardized rate does not

necessarily indicate a corresponding decline in turtle abundance, and conversely the higher rates in early monitoring years cannot be interpreted directly as evidence of greater historical turtle abundance. The modest increase in descriptive rates after the 2017 minimum further shows that the trajectory was not strictly monotonic, and future analyses incorporating environmental covariates, spatial redistribution of fishing activity, fleet composition and documented changes in fishing practice would be needed before stronger causal conclusions could be drawn.

4.3 Taxonomic resolution and release condition

The very limited species-level identification of captured turtles is one of the most important biological constraints of the study. With 98% of captures reported under the aggregate category Turtle spp., the pooled spatial interaction-priority pattern cannot be confidently attributed to any individual marine turtle species, which is important given that different species can differ substantially in habitat use, movement behavior, life-history stage and gear vulnerability. Pooling unidentified turtles is appropriate for estimating the overall fishery-interaction pattern when taxonomic information is unavailable, but it limits the ecological specificity of any resulting management interpretation. The absence of formal species-specific hotspots should be understood as a consequence of inadequate analytical support rather than as evidence that named species were at low risk or absent from the monitored fishery, a limitation also identified in the earlier exploratory Blue Corridors analysis from the same programme (Abdul Razzaque et al., 2025). Immediate release condition (3.96% released dead among single-turtle events) similarly requires careful interpretation. It describes capture-conditional condition at release only, and should not be interpreted as delayed mortality, post-release mortality, total fishing mortality or long-term survival following a gillnet interaction. The absence of an association between measured body size and release condition, and the modest but non-significant differences among fishing phases, suggest that immediate release outcomes were relatively

stable across the biological and operational strata examined, though the declining trend in the year-only sensitivity model warrants continued monitoring. Determining true fishing mortality, as distinct from the fate observed at release, would require dedicated post-release survival studies.

4.4 Vessel-level heterogeneity reflects operational structure

Vessel-level heterogeneity in recorded turtle interactions was considerably greater than heterogeneity in monitoring effort, with a small number of vessels accounting for a disproportionate share of both turtle individuals and turtle-positive operations. However, because vessels with comparatively high observed interaction rates were also monitored predominantly in the earlier, higher-interaction years of the programme, vessel-level differences likely reflect combinations of monitoring year, fishing location, fishing method and operational practice rather than a persistent, intrinsic vessel-specific propensity for turtle interaction. A comparable pattern was reported for dolphin bycatch within the same fleet, where bycatch was more strongly associated with operational and temporal factors than with vessel identity or geographic location alone (Abdul Razzaque et al., 2024a). From a management perspective, this suggests that mitigation and monitoring would be more appropriately focused on combinations of vessel behaviour, fishing location, timing and operational practice than on labelling individual vessels as inherently high risk. The vessel-block bootstrap, in which recurrence of the four priority cells remained comparatively high (63.9–95.5%) despite explicitly accounting for vessel clustering, supports the conclusion that the spatial pattern is not an artefact of a small number of vessels alone. Further analyses linking vessel identity to spatial use, fishing method, temporal coverage and gear characteristics could help identify which operational features are most strongly associated with elevated interaction rates.

4.5 Spatial-reference uncertainty is consequential at management scales

The coordinate-source and SET–HAUL sensitivity analyses demonstrate that spatial-reference choice can materially affect assignment at the IOTC 1×1 scale. Although typical SET–HAUL displacement (median 10.04 km) was moderate relative to the nominal dimensions of a one-degree grid cell, a meaningful proportion of operations (13.1% overall, 14.0% of turtle-positive operations) changed analytical cell when the alternative endpoint was used, and a comparable proportion changed cell under the historical-coordinate comparison. This is expected because operations located near grid boundaries can shift into an adjacent cell after relatively small positional changes, meaning that the proportion of operations changing cell assignment is at least as informative as the absolute displacement distance for fine-scale spatial inference. Standardizing the operation-level reference to SET coordinates was therefore important for maintaining a consistent zero-inclusive denominator that could be applied to both turtle-positive and zero-turtle operations, with HAUL retained as the preferred descriptive reference for biological turtle-event information. Neither reference, however, represents the exact point at which a turtle initially became entangled. The SET marks the beginning of the monitored operation and HAUL the retrieval/end-of-operation reference, and the true entanglement position may lie between or around these operational endpoints. The hotspot and interaction-priority maps should therefore be interpreted as SET-referenced spatial patterns of monitored fishery interactions rather than as maps of exact turtle-capture locations, and their boundaries should not be treated as precise biological limits; more precise spatial inference would require improved recording of fishing-operation positions and, ideally, direct georeferencing of individual turtle interactions.

4.6 Interpretation of the four-cell interaction-priority area

The identification of four contiguous IOTC 1×1 cells represents the strongest spatial result of the study. the four cells together contained only 20 of 907 turtle individuals in the primary

spatial population. Its importance derives not from elevated raw turtle counts but from concordance between two complementary operation-standardized endpoints, turtle-individual burden and turtle-positive-operation occurrence, and from the local, neighborhood-based nature of the Getis–Ord G_i^* statistic, which evaluates statistically elevated local clustering relative to the fitted conditional null rather than simply the number of turtles contained in a focal cell. Close agreement between the primary operation-based analysis and the fishermen-reported-net-km sensitivity (Jaccard indices of 0.80 for burden and 1.00 for occurrence, and a Spearman correlation of 0.997 between the two rate surfaces) further strengthens confidence that the core spatial result does not depend solely on defining one fishing operation as the primary exposure unit. At the same time, temporal disaggregation shows that the pooled four-cell configuration was not reproduced as an identical formal hotspot pattern in every year or fishing phase, so the connected area is best interpreted as an integrated multi-year fishery-interaction priority rather than a fixed hotspot continuously occupied throughout the study period. The relationship with the earlier exploratory Blue Corridors analysis from the same programme (Abdul Razzaque et al., 2025), which used turtle-weighted kernel-density surfaces, H3 aggregation and geodesic connections while explicitly acknowledging heterogeneous fishing effort and the absence of effort-standardized denominators as limitations, is therefore best viewed as complementary. The present study refines that earlier exploratory spatial hypothesis by identifying where interactions remain elevated after explicit standardization for monitored fishing exposure and formal statistical testing, but because both analyses derive from the same broader monitoring programme. They should not be treated as independent confirmation of one another.

4.7 Implications for Blue Corridor research

The connected interaction-priority area provides a focused spatial hypothesis for future Blue Corridor research, but fishery-interaction priority and biological connectivity are

fundamentally different quantities. The present analysis identifies where turtle interactions were elevated relative to monitored fishing exposure, not that turtles moved repeatedly among the connected cells or that the area functions as a migratory pathway. Fishery-interaction hotspots can arise through several, potentially overlapping, processes (elevated turtle occurrence, concentrated fishing activity, spatial overlap between turtles and fishing operations, and variation in vulnerability to gillnet gear) and operation standardization substantially improves interpretation by accounting for monitored fishing exposure, but elevated interaction rates still do not, by themselves, provide direct evidence of biological movement between neighbouring cells. The main contribution of the present analysis to Blue Corridor research is therefore spatial prioritization for independent biological validation. The four-cell area provides a geographically explicit location where future movement studies could be concentrated to test whether the fishery-interaction pattern corresponds to biologically meaningful connectivity. Suitable independent evidence could include satellite telemetry capable of documenting repeated turtle movement through or among the priority cells, conventional tagging or mark–recapture data, genetic or population-connectivity analyses, dedicated vessel- or aerial-based turtle surveys, and other independent movement or habitat-use datasets capable of distinguishing transient occurrence from structured connectivity (Kot et al., 2023; Madden et al., 2025). The present spatial pattern is dominated by the aggregate reported category Turtle spp., such independent movement information should, where possible, be species specific and should consider seasonality and interannual variability rather than testing only whether turtles occur somewhere within the four-cell area. Until such independent evidence is available, the connected area should remain described as a marine turtle–gillnet interaction-priority area and, at most, a candidate spatial hypothesis for Blue Corridor validation.

4.8 Management implications

The connected four-cell interaction-priority area provides a practical spatial focus for fisheries management because it identifies where the strongest operation-standardized evidence of marine turtle–gillnet interaction occurred within the monitored fishery, and can support targeted monitoring, focused engagement with fishing vessels and evaluation of bycatch-reduction measures without requiring the area to be interpreted as biologically important turtle habitat or a confirmed movement corridor. Where monitoring resources are limited, managers could combine intensified coverage within the high-evidence priority area with continued surveillance elsewhere to detect future shifts in the spatial distribution of interactions, while ensuring that cells with insufficient statistical support are not treated as low-risk, since this reflects a gap in available data rather than evidence of low interaction risk. Maintaining zero-inclusive, operation-level monitoring is fundamental to this framework, because recording only turtle encounters would prevent estimation of interaction rates and distinguishing genuinely elevated risk from areas that simply experienced greater fishing activity. Electronic monitoring, already piloted successfully within this fishery to document fishing operations and verify crew-based records (Abdul Razzaque et al., 2024b). It offers a mechanism for strengthening future data verification, species identification and operational coverage, particularly within the priority area, while continued fisher-led safe-handling and release training (Abdul Razzaque et al., 2020) should be maintained as a complementary but analytically distinct measure, since improving immediate release condition does not necessarily reduce the probability of turtle capture. Management action should therefore distinguish three related but separate objectives i) reducing the probability of turtle–gillnet interaction, ii) improving outcomes when interactions occur, and iii) strengthening monitoring and verification. All of which the spatial framework developed here can help prioritize, while preserving the distinction between fishery-interaction evidence and biological importance.

4.9 Study limitations and priorities for future research

Several limitations should be considered when interpreting these findings. As a trained crew-based monitoring dataset rather than an independent scientific-observer programme, the analysis cannot estimate turtle abundance, density or exact entanglement location, and reporting consistency, taxonomic identification and net-length recording may have varied over the study period and among vessels and crew. Species-level interpretation remains the most important biological limitation, and improving species identification, ideally through photographic verification, targeted crew training or, where feasible, genetic sampling, should be a priority for future monitoring, alongside continued standardized recording of body-size and release-condition information. Electronic monitoring integration, further standardization of biological documentation, and continued zero-inclusive operation-level recording will be important for confirming whether the identified interaction-priority area persists beyond the 2012–2019 study period and for detecting future changes in its spatial extent. Finally, independent movement-based evidence such as satellite telemetry, tagging or mark–recapture, genetic analyses, or dedicated ecological movement studies, ideally species-specific and covering multiple seasons will remain the essential next step for determining whether the identified fishery-interaction priority area corresponds to a biologically meaningful marine turtle Blue Corridor.

5. Conclusions

This study developed a zero-inclusive, operation-standardized assessment of marine turtle interactions in Pakistan's tuna gillnet fishery using eight years of crew-based observer data. Operation-standardized interactions declined markedly over the monitoring period, with no independent fishing-phase effect once a year was accounted for. Biological interpretation was constrained by limited species-level identification, and the release-outcome analysis supported

inference only about immediate condition at release, not delayed mortality, post-release survival or total fishing mortality.

Formal spatial analysis identified four contiguous IOTC 1×1 cells as the strongest marine turtle–gillnet interaction-priority area within the monitored fishery, supported by two complementary endpoints and remaining comparatively stable under leave-one-year-out analysis, fishing-method omission, operation and vessel bootstrap resampling, and an alternative effort definition. This convergence provides strong internal support for prioritizing the area for enhanced monitoring, bycatch-mitigation evaluation and continued observation, but the area should be interpreted strictly as a fishery-interaction priority. The analysis does not establish turtle abundance, density, habitat preference, exact entanglement location or biological movement connectivity, and spatial contiguity alone is insufficient to demonstrate a migration corridor. Confirmation of a biological Blue Corridor would require independent movement or connectivity evidence such as satellite telemetry, tagging, mark–recapture, genetic analyses or dedicated ecological movement studies.

The study provides a reproducible framework for converting long-term fishery-dependent monitoring data into zero-inclusive, operation-standardized and spatially explicit interaction evidence while preserving clear limits on ecological interpretation. Continued zero-inclusive operation-level monitoring, improved species verification, standardized biological documentation, strengthened electronic monitoring and independent turtle-movement data will be important for determining whether the identified interaction-priority area persists beyond the 2012–2019 study period and whether it corresponds to biologically meaningful marine turtle connectivity.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The monitoring data analyzed in this study contain vessel-identifying information and are subject to confidentiality agreements with participating fishing vessels and communities. De-identified summary data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to WWF-Pakistan data-sharing policies.

Ethics Statement

This study used the data of the fishery-independent observations recorded by trained crew-observers/ skippers during routine tuna-gillnet operations in Pakistan's EEZ (2012–2019). Data collection involved non-invasive observation and handling of incidentally captured marine turtles by trained fishing crew following WWF-Pakistan safe-handling and release protocols (Abdul Razzaque et al., 2020), designed to minimise stress and injury and to maximize survival of released individuals. No experimental manipulation of animals was conducted for the purposes of this study. Vessel identifiers and personal information were anonymized before analysis.

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