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CASE STUDY

Environmental implications of fisheries modernization revealed by assemblage restructuring and fishing-gear dynamics

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ABSTRACT

BACKGROUND AND OBJECTIVES: Fisheries modernization can improve landing efficiency, market connectivity, and coastal livelihoods, but may also alter fishing practices and the biological composition of resources entering landing systems. Consequently, appraising the ecological dimensions of modernization necessitates multifaceted metrics that extend well beyond conventional industrial output and financial performance. The study objectives were to examine changes in landed-fish assemblages in Biak Numfor, eastern Indonesia, using harmonized fisheries records from 2021 to 2024, with monthly and fishing-gear analyses for 2023 and 2024.

METHODS: Presence–absence matrices quantified species richness, Jaccard and Sørensen dissimilarities, turnover, principal coordinates analysis, permutational multivariate analysis of variance, multivariate dispersion, and indicator taxa. Employing sensitivity frameworks stratified by gear type alongside common-gear evaluations enabled the clear differentiation between the expansion of fishing equipment and internal structural shifts within comparable operational methods.

FINDINGS: Harmonized annual richness increased from 32 taxa in 2023 to 52 taxa in 2024, while mean monthly richness increased from 24.92 ± 0.79 to 35.33 ± 3.31 taxa per month (paired Wilcoxon signed-rank test, p-value = 0.000488). Annual Jaccard and Sørensen dissimilarities were 0.623 and 0.452, respectively, with turnover of landed taxa accounting for approximately 62 percent of Sørensen dissimilarity. Monthly assemblage structure differed significantly between years after controlling for calendar month (permutational multivariate analysis of variance, pseudo-F = 51.35, p-value = 0.000488, partial coefficient of determination = 0.824), although multivariate dispersion also differed significantly (F = 7.34, p-value = 0.000488). Fishing gear was the dominant measured correlate of assemblage structure (pseudo-F = 66.40, p-value = 0.0005, partial coefficient of determination = 0.721). A smaller year-associated effect persisted after controlling for gear and month (pseudo-F = 11.88, p-value = 0.0005, partial coefficient of determination = 0.103). Limiting the analytical scope to five mutually shared gear types eliminated disparities in species richness, although profound multivariate distinctions persisted. Among the 29 novel taxa documented in 2024, 28 were localized within tuna-longline and/or large-pelagic-purse-seine assemblages, conversely, richness experienced a contraction in non-port landings, the only landing category common to both sampling periods.

CONCLUSION: Modernization-period change is better interpreted as restructuring of the fishing and landing system than as a simple increase in marine biodiversity. Fisheries modernization can be evaluated by integrating gear-sensitive assemblage monitoring with standardized taxonomic and landing-site datasets, thereby decoupling alterations in resource utilization from shifts in operational practices and reporting procedures.

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INTRODUCTION

Coastal fisheries modernization is increasingly promoted as a strategy to improve landing efficiency, product quality, market connectivity, and the economic performance of fishing communities. Investments in fish landing facilities, cold storage, ice production, transportation, and market infrastructure can improve product handling, facilitate market access, and reduce post-harvest losses, particularly in small-scale fisheries (Arista *et al.,* 2022; Mramba and Mkude, 2022). In Indonesia, this national trajectory finds contemporary expression through the Kampung Nelayan Merah Putih (KNMP) initiative, which embeds fisheries infrastructure enhancement directly at the artisanal community scale. Its infrastructure includes, among others, fishing-vessel landing facilities and jetties, cold-chain infrastructure for handling and storage, and facilities supporting processing, distribution, and marketing of fishery products. Such capital allocations are projected to mitigate post-harvest depreciation and enhance market connectivity; deficiencies in refrigeration, preservation, transportation, and logistical infrastructure are recognized primary drivers of physical, qualitative, and economic attrition across marine supply chains (Abelti and Teka, 2024; Mramba and Mkude, 2022). However, improved infrastructure may also alter the operational characteristics of fisheries by facilitating vessel activity, improving storage capacity, expanding market opportunities, and enabling catches to be landed and marketed more efficiently. Furthermore, empirical insights from fisheries value-chain investigations indicate that processing infrastructure, refrigeration networks, logistical distribution, and broadened market conduits critically shape the economic viability accessible to fishing enterprises (Bjørndal *et al.,* 2015). From an environmental perspective, these changes are important because fisheries infrastructure is not environmentally neutral. Improved landing, cold-storage, distribution, and marketing capacity can alter incentives and the economic feasibility of fishing activity, particularly where improved market connectivity makes additional species or fishing grounds commercially accessible. In coral-reef fisheries, for example, increased market access has been associated with expansion of fishing pressure, emphasizing that changes in market connectivity can interact with fishing behavior and resource exploitation (Carvalho, 2020). Enhanced operational capacity can empower fishers to adjust their temporal allocation or spatial reach, deploy or intensify specific gear configurations, exploit previously underexploited fishing areas, or diversify their catch portfolio to include a wider spectrum of commercially lucrative species. Consequently, modernization may lead not only to increased production but also to exploitation of a wider range of species or greater pressure on particular target species. The environmental performance of fisheries modernization therefore cannot be assessed solely through production volume, economic value, or infrastructure utilization; it also requires examination of how the biological composition of resources entering the landing system changes over time. This distinction is particularly important because fisheries landings reflect an interaction between ecological availability and human exploitation. Fisheries-dependent data integrate information on catch composition with fishing location, gear type, fisher behavior, season, and operational decisions, meaning that observed landing composition is simultaneously shaped by ecological and fishing processes (Wibisono *et al.,* 2021; Herdiana *et al.,* 2024). Accordingly, landing sites serve as the critical spatial nodes orchestrating the complex interactions among fishing vessels, gear assemblages, grounds, commercial markets, surveillance frameworks, and harvested aquatic taxa. An increase in the number of taxa recorded at a landing site may consequently result from a broader fishing range, increased gear diversity, altered targeting behavior, improved reporting, or changes in ecological availability. Accordingly, higher landed-species richness should not automatically be interpreted as an improvement in

marine biodiversity. Instead, landed-fish assemblages can be treated as fisheries-dependent socio-ecological indicators of how fishing systems interact with biological resources. Indonesian small-scale fisheries illustrate this complexity: catch composition may vary substantially among fishing methods, fishing depths, seasons, years (y) and fishing grounds (Humphries *et al.,* 2019; Herdiana *et al.,* 2024). Presence-absence community datasets establish a robust foundation for such evaluations by delineating which taxa enter the fishery while simultaneously mitigating vulnerability to potential discrepancies in reported catch weight or economic valuation. Incidence-based beta-diversity approaches are particularly suitable for distinguishing changes in species identity from changes attributable merely to differences in species richness (Baselga, 2010) (Baselga and Leprieur, 2015). Beta-diversity approaches can therefore distinguish simple species accumulation from species replacement. Turnover-dominated change signifies that variations among biological assemblages' stem primarily from taxonomic substitution, whereas nestedness-resultant modification implies that depauperate assemblages progressively constitute a strict subset of their more species-rich counterparts (Baselga, 2010). Jaccard- and Sørensen-based measures have been widely applied to fish assemblages and can be partitioned into replacement/turnover and nestedness components to investigate mechanisms underlying compositional differences (Huang *et al.,* 2019). Multivariate analysis can then evaluate whether temporal differences reflect broader restructuring of the landed assemblage rather than isolated changes in species richness. Permutational multivariate analysis of variance (PERMANOVA), for example, provides a permutation-based framework for testing differences in multivariate composition using a chosen dissimilarity measure, while ordination can be used to visualize the corresponding compositional patterns (Anderson, 2017a). Given that variations in multivariate dispersion can confound the interpretation of dissimilarity-based analyses, dispersion metrics ought to be examined concurrently with compositional divergences (Anderson, 2017b). Fishing gear must also be considered explicitly because gear selectivity acts as a major filter between marine communities and landed catches. Various fishing gears sample distinct segments of aquatic communities, selectively filtering taxa on the basis of habitat utilization, trophic guilds, mobility patterns, somatic size, schooling tendencies, and associated functional traits (Carvalho *et al.,* 2021). Consequently, species that are not vulnerable to the gears in use, are discarded at sea, are consumed or sold before recording, or are not reported remain absent from landing records regardless of their occurrence in the marine environment. In an Indonesian multispecies coral-reef fishery, handlines and spearguns showed limited overlap in dominant catches and targeted different ecological groups, demonstrating that fishing gears can generate markedly different landed assemblages even within the same broader fishery (Humphries *et al.,* 2019). Consequently, shifts in aggregate community composition can manifest purely as a function of altered relative proportions among deployed fishing gears. Conversely, assemblage composition may change within the same gear even where species richness remains similar. Research on Indonesian small-scale fisheries has shown that catch composition within individual fishing methods can vary significantly with fishing depth, season, and year, indicating that controlling for gear alone does not necessarily remove temporal and spatial variation in resource use (Herdiana *et al.*, 2024). Isolating these underlying mechanisms remains imperative when appraising modernization; expansion of the gear repertoire may signal a broader scope of harvesting opportunities, whereas taxonomic turnover within analogous gear categories implies profound shifts in resource exploitation patterns. These questions are particularly relevant in eastern Indonesia, where highly diverse tropical

marine ecosystems support fisheries characterized by artisanal, small-scale, multispecies, and technologically differentiated fishing operations. Empirical studies across Indonesia indicates that artisanal fisheries frequently encompass extensive suites of species and gear configurations, with catch composition fluctuating significantly according to deployed gear types and prevailing operational contexts (Humphries *et al.,* 2019; Herdiana *et al.,* 2024). Biak Numfor provides an appropriate case for examining this interface In Biak Numfor, KNMP-type fishing-village modernization was implemented at the Samber–Binyeri fishing settlement in Yendidori District, which was officially inaugurated on 23 November 2023 (Setkab, 2023). The intervention provided integrated fisheries facilities, including landing facilities, an ice plant, cold storage, a fuel station, a vessel-repair workshop, a fishers' cooperative, and processing and marketing facilities. These facilities predominantly accommodated the artisanal inshore fleet—comprising outboard-propelled craft under 5 gigatons (GT) deployed for day-trip handlining, trolling, and kite-lining, whereas landings originating from larger commercial vessels utilizing tuna longlines and purse seines were documented at Pelabuhan Perikanan (PP), Fandoi, the district fishing port. Accordingly, the records for 2021–2022 represent the period before the intervention, whereas the detailed 2023–2024 analyses bracket the start of the intervention in late 2023. Fishery archives comprise documentation of landed taxa, gear configurations, fishing vessels, and—in more recent temporal intervals—monthly landing statistics. These records provide a pre-modernization baseline, affording a methodological framework to characterize temporal restructuring in the landed assemblage immediately prior to subsequent fisheries-infrastructure expansion. However, explicit landing-port identification is not consistently available before 2024, and taxonomic and operational resolution differs among years. These limitations preclude a simple port-level before-after causal assessment and caution against attributing observed assemblage changes directly to KNMP infrastructure. A more defensible question is whether the recorded landed-fish community underwent significant transformation across the study period, the magnitude of such structural restructuring, and the degree to which these shifts correlated with alterations in operational practices and gear configurations. Presence-absence community matrices are used to quantify species richness, Jaccard and Sørensen beta diversity, turnover and nestedness, principal coordinates analysis (PCoA), PERMANOVA, multivariate dispersion, and indicator taxa. The combination of incidence-based beta diversity and multivariate analyses allows temporal differences to be evaluated both in terms of species replacement and whole-assemblage structure (Baselga, 2010; Anderson, 2017a). Fishing gear is explicitly incorporated as a structuring factor, together with a common-gear sensitivity analysis to distinguish expansion of the fishing-gear portfolio from compositional changes within fishing methods represented in both years. It is hypothesized that if fisheries modernization and concomitant shifts in operational opportunities principally widen the exploitation and landing domain, the recorded taxonomic spectrum will diversify, resulting in the localized concentration of newly documented taxa within newly introduced gear categories. Conversely, if restructuring extends beyond gear expansion, significant compositional differences should remain within fishing gears common to both periods. This analytical framework permits fisheries modernization to be appraised beyond mere infrastructural development or output increases, focusing instead on how shifts in fishing capacity and operational configuration manifest within the biological resources recruited into the fishery system. The study addresses three interconnected questions: 1) whether the observation period was accompanied by changes in landed-species richness and assemblage composition; 2) whether these changes were characterized primarily by

species turnover rather than simple species accumulation; and 3) whether fishing-gear structure explains the observed temporal differences or whether compositional change persists among comparable gears. This study aims to evaluate spatiotemporal changes in landed-fish assemblages in Biak Numfor using taxonomically harmonized fisheries records from 2021–2024, with detailed monthly and fishing-gear analyses for 2023–2024.

MATERIALS AND METHODS

Study location, design, and data preparation

The study was conducted in Biak Numfor Regency, Papua, eastern Indonesia, an archipelagic area situated within the western Pacific region and characterized by strong dependence of coastal communities on marine fisheries (Fig. 1). Biak Numfor is surrounded by productive tropical marine waters that support diverse coastal, reef-associated, and pelagic fisheries and lies within Fisheries Management Area of the Republic of Indonesia 717 (WPPNRI 717). The regional fisheries framework incorporates a diverse array of gear configurations and vessel categories targeting an extensive spectrum of demersal, reef-associated, and pelagic stocks, rendering the area exceptionally well-suited for evaluating temporal dynamics in landed-fish assemblages. The study focused on fisheries landing records from Biak Numfor during 2021–2024, with detailed monthly analyses for 2023–2024, a period encompassing changes in the local fishing and landing system associated with fisheries modernization. Temporal changes in landed-fish assemblages in Biak Numfor, Papua, were evaluated using fisheries production records for 2021–2024. The primary analytical focus centers on the assemblage of taxa recorded in fisheries landings rather than the marine ichthyofauna inhabiting open waters; consequently, the methodological design remains observational and fisheries dependent. Differences in the recorded assemblage may reflect changes in fishing effort, fleet and gear composition, fishing grounds, landing-site operations, market demand, regulations, reporting practices, or ecological and climatic variability, rather than changes in the fish community alone. These potential confounding factors were methodologically controlled by designating gear type as a structural covariate and restricting permutation routines within specific calendar months, whereas discrepancies in taxonomic documentation were minimized through rigorous data harmonization. Annual data for 2021–2024 were used to characterize changes in the district-level species pool, whereas monthly and fishing-gear analyses were restricted to 2023–2024 because monthly information was unavailable for earlier years. Records were filtered to BIAK NUMFOR and included year, month where available, port, fishing gear, vessel information, local/common name, scientific name, and Food and Agriculture Organization (FAO) or Aquatic Sciences and Fisheries Information System (ASFIS) code. Catch weight and economic valuation were excluded as metrics of abundance due to temporal inconsistencies in reporting resolution across study years. Monthly records and fishing trips were available only for 2023–2024, whereas 2021–2022 records were annual compilations without effort information, and fishing days were not recorded in any year; effort-related comparisons were therefore restricted to 2023–2024. Scientific names were harmonized conservatively and used as the primary taxonomic key. Of 1,491 records for 2021–2024, one required correction of name formatting, and 66 with 4.4 percent (%) were aggregate categories or genus-level records that were excluded from species-level analyses. Because outdated synonyms and orthographic variants matched no other taxa within the dataset, they exerted no influence on species richness; consequently, taxonomic identifications were retained as originally reported given the infeasibility of specimen-level verification was not possible. The resulting harmonized dataset contained 73 species-level taxa. To ascertain sensitivity to inter-annual

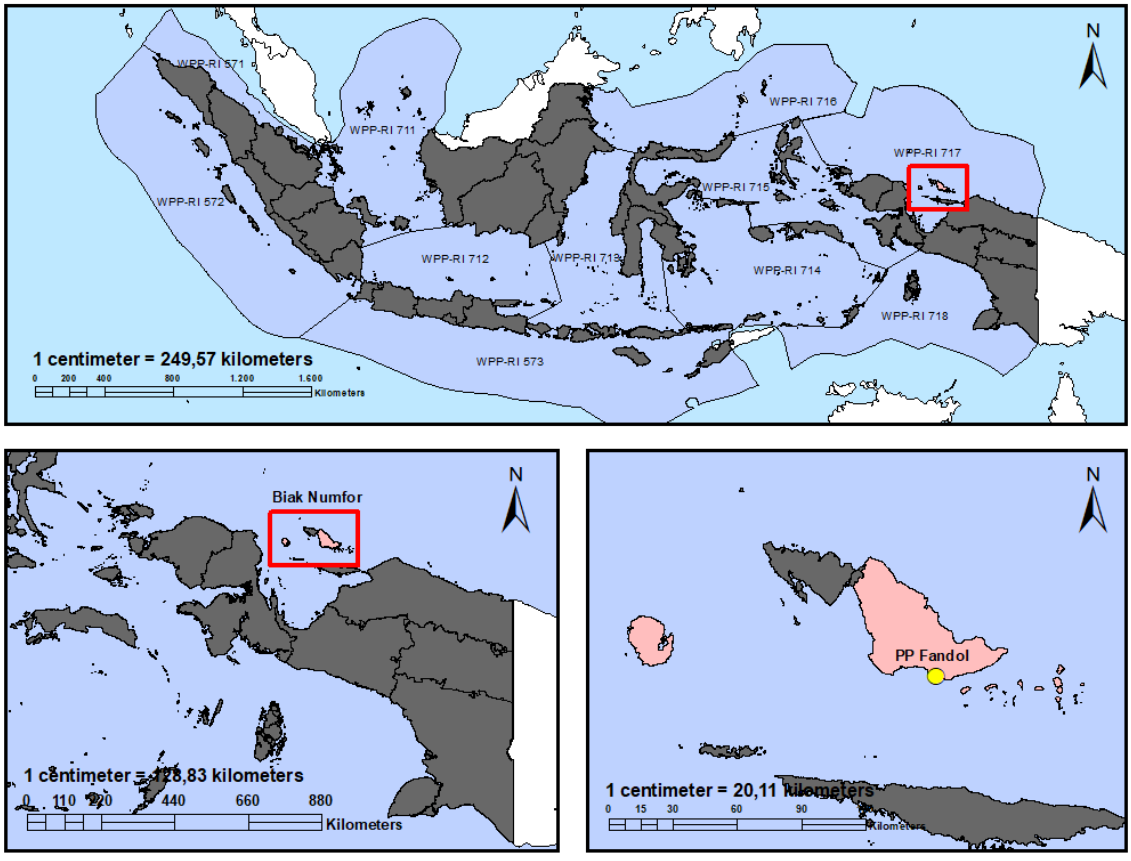

Fig. 1: Geographical location of the study area in Biak Numfor Regency, eastern Indonesia

discrepancies in taxonomic resolution, analyses of annual and monthly richness, beta diversity, and PERMANOVA were replicated following the aggregation of taxa to the genus level. The same analyses were repeated after excluding the seven taxa that occurred in only one year × month unit.

Presence–absence matrix and species richness

Analyses of the landed assemblage were based on species presence–absence. Multiple records of the same species within a sampling unit were collapsed into a single occurrence. Sampling units were Year for annual analyses, year × month for monthly analyses, and year × month × gear for gear-specific analyses. Annual pools were used descriptively rather than as statistical replicates. Monthly and gear-specific units were treated as repeated, non-independent observations of the same fishery; all inferential tests were therefore paired or blocked by calendar month, and p-values were interpreted as the consistency of between-year differences across the 12 paired months rather than as inference from independent replicates. Observed richness was quantified as the total count of species recorded within each individual sampling unit, aligning with standard incidence-based community frameworks, using Eq. 1 (Baselga, 2010):

$$S_i = \Sigma_{j=1}^{P} x_{ij} \quad (1)$$

Where: x_{ij} = 1 when species j occurred in sampling unit i and 0 otherwise, and P is the total number of harmonized species. Monthly richness was summarized by mean, standard deviation, minimum, and maximum. Corresponding months

in 2023 and 2024 were compared using a two-sided paired Wilcoxon signed-rank test (Bangdiwala, 2013):

Beta diversity, turnover, and nestedness

Pairwise compositional dissimilarity was calculated from presence–absence data. For any pair of biological assemblages, let a denote the number of shared species, b represents the species restricted exclusively to the first assemblage, and c signify the species occurring solely within the second assemblage. Jaccard dissimilarity was used as the principal measure of assemblage dissimilarity, using Eq. 2 (Baselga and Leprieur, 2015):

Jaccard beta-diversity dissimilarity (βJAC) = (b + c)/(a + b + c) (2)

Sørensen dissimilarity was additionally calculated because it allows additive partitioning into turnover and nestedness-resultant components, using Eq. 3 (Baselga, 2010):

Sørensen beta-diversity dissimilarity (βSOR) = (b + c)/(2a + b + c) (3)

Following the Baselga framework, species turnover was quantified using Simpson dissimilarity, using Eq. 4 (Baselga, 2010):

Simpson turnover component of Sørensen beta diversity (βSIM) = min(b,c)/[a + min(b,c)] (4)

The nestedness-resultant component was then calculated as the difference between total Sørensen dissimilarity and turnover, using Eqs. 5 and 6 (Baselga, 2010):

βSNE = βSOR − βSIM (5)

βSOR = βSIM + βSNE (6)

These metrics were calculated for annual species pools and between consecutive months. Higher βSIM relative to βSNE was interpreted as compositional change dominated by replacement of taxa in the recorded landed assemblage rather than differences attributable to nested species subsets (Baselga, 2012); it does not by itself indicate species replacement in the underlying marine community.

Multivariate assemblage analysis

PCoA based on Jaccard dissimilarity was used to visualize differences in assemblage composition among sampling units (Saeed *et al.,* 2018). PCoA were generated for monthly fish communities, as well as for subsets restricted to gear categories represented across both 2023 and 2024. Variations in community composition were subsequently evaluated via PERMANOVA. PERMANOVA partitions distance-based variation and assesses significance through permutation without requiring multivariate normality, using Eq. 7 (Anderson, 2001):

Pseudo-F = (SSterm/dfterm)/(SSresidual/dfresidual) (7)

Where: SS and df represent the sums of squares and degrees of freedom for the focal model term and residual variation, respectively. Monthly assemblages were modeled D ~ Month + Year, where D represents the Jaccard distance matrix derived from the 24 years × month assemblages; the main effect of Year was evaluated conditionally upon Month, with Year labels permuted strictly within corresponding calendar months. With 12 paired months, only 2^{12} = 4,096 permutations are possible; all were enumerated, so p = 0.000488 is the smallest attainable value (Anderson, 2001; Anderson, 2017b). Common-gear assemblages (n = 120) were analyzed with D ~ Year + Month + Gear, testing Gear and Year conditional on the other terms using 1,999 restricted permutations that preserved Year, Month, and Gear structure. Partial R^2 was calculated relative to the sum of the focal-term and residual sums of squares, and unique total R^2

relative to the total sum of squares. Multivariate dispersion was assessed using permutational analysis of multivariate dispersions (PERMDISP) because PERMANOVA may respond to differences in within-group dispersion as well as differences in group centroids (Anderson, 2006; Anderson and Walsh, 2013). Consequently, a significant PERMANOVA result coupled with a significant PERMDISP outcome was interpreted with caution, signaling broader multivariate heterogeneity in community structure rather than a localized shift in assemblage centroid alone.

Fishing-gear analysis

The gear portfolio comprised five gears in 2021, six in 2022, five in 2023, and seven in 2024. Fishing-gear names were harmonized between 2023 and 2024 before gear-stratified analyses. The shared-gear subset consisted of fixed gillnets, handlines, traps, trolling lines, and small pelagic purse seines. Sampling intensity was quantified via the frequency of landing records, active months, and fishing excursions documented for each respective gear type and annual interval. Because presence–absence data do not account for sampling intensity, differences among gears and years may partly reflect unequal numbers of records rather than genuine changes in occurrence. A common-gear sensitivity analysis was conducted after excluding gears not represented in both years. This analytical approach decoupled community shifts attributable to the expansion of the recorded gear inventories from compositional variations transpiring within analogous fishing methodologies. Mean monthly richness, matched-month Jaccard dissimilarity, and paired PERMANOVA were evaluated for each common gear.

Indicator taxa

Taxa associated with years, or fishing gears were identified using the Indicator Value framework, which combines specificity and fidelity of a species to a predefined group. Specificity (A) characterizes the degree of concentration of a taxon within a designated group, whereas fidelity (B) denotes its relative occurrence or frequency within that same assemblage group. Indicator Value combines these two components into a single measure of association, using Eq. 8 (Sanchez *et al*., 2022):

$$\text{Indicator value (IndVal)}_j g = \sqrt{(A_j g \times B_j g)} \quad (8)$$

Where: $A_j g$ is the specificity and $B_j g$ is the fidelity of taxon j to group g. Higher values indicate stronger associations between a taxon and the focal group. Indicator-value approaches combine information on exclusivity and occurrence frequency when identifying taxa characteristic of groups (Dufrêne and Legendre, 1997; De Cáceres and Legendre, 2009). Temporal associations with year were evaluated using permutations constrained within individual calendar month, whereas gear-type associations were assessed via permutations restricted to specific year × month blocks. Year indicators were tested on the same 24 y × month units used in PERMANOVA, with all 4,096 within-month permutations enumerated, whereas gear indicators were tested on the 120 y × month × gear units of the common-gear subset using 1,999 permutations. No taxa were excluded for rarity, and all 73 harmonized taxa were included in the Benjamini–Hochberg correction, although only 61 and 42 taxa occurred in the year and gear datasets, respectively, making the correction slightly conservative. With 12 months per year, the smallest attainable p-value for year indicators was 0.00049, and rarely recorded taxa could not attain significance.

Multiple-testing correction

Because indicator species analyses entailed simultaneous testing across multiple taxa, permutation-derived p-values underwent false discovery rate correction utilizing the Benjamini–Hochberg procedure. For m hypotheses with ordered p-values, the adjustment is based Eq. 9 (Thissen *et al.,* 2002; Jafari and Ansari-Pour, 2019):

$$q^*(i) = (m/i) \times p(i) \quad (9)$$

Where: i is the rank of the ordered p-value and m is the total number of hypotheses. Adjusted values were constrained to be monotonic, and taxa with $q < 0.05$ were considered statistically supported indicators. False-discovery-rate control is preferable to interpreting large numbers of unadjusted individual tests (Benjamini and Hochberg, 1995).

Apparent species gains and statistical interpretation

Species recorded in the 2024 annual pool but absent from the harmonized 2023 pool were classified as apparent species gains. To differentiate newly documented taxa from historically present yet undetected species, apparent gains were categorized according to their prior record during 2021–2022, their monthly occurrence frequency in 2024, and their restriction to gear types absent from the 2023 dataset. This analysis was descriptive and was not interpreted as evidence that modernization or changes in fishing gear caused the ecological appearance of those species. Statistical significance was evaluated at $\alpha = 0.05$, with $q < 0.05$ used for indicator taxa after false-discovery-rate correction. Effect sizes and dissimilarity measures were considered together with p-values. Owing to inter-annual variations in reporting resolution, port identification, and fishing-gear representation, empirical patterns were interpreted strictly as temporal and fishing-system associations within landed-fish assemblages rather than as direct causal effects on marine biodiversity.

RESULTS AND DISCUSSION

Taxonomically harmonized richness and temporal beta diversity

All results are based on presence–absence data and therefore indicate whether a taxon was recorded, not whether its catch weight, abundance, or relative importance changed. After harmonizing taxonomic labels across the annual fisheries workbooks and excluding aggregate or non-species categories, the Biak Numfor landed-fish species pool comprised 35 taxa in 2021, 36 in 2022, 32 in 2023, and 52 in 2024. Consequently, the apparent upward trend observed in 2024 persisted following internal taxonomic harmonization, albeit at a magnitude smaller than that indicated by unstandardized local nomenclature. This distinction is important because taxonomic inconsistencies and differences in identification resolution can alter estimates of species richness and community composition, particularly when datasets are compared across surveys or years (Meredith *et al.,* 2019; Cayuela *et al.,* 2011). When tuna longline and large pelagic purse seine were excluded, the 2024 species pool contained 32 taxa, identical to 2023 and lower than in 2021–2022 (35–36 taxa), indicating that these two gears accounted for the entire annual increase. Fisheries-dependent landings reflect not merely ecological availability but also fishing effort, targeting behavior, spatial allocation of fishing grounds, market demand, and shifts in the range of exploited resources; consequently, variations in landed-species composition cannot be interpreted uncritically as direct equivalents of structural changes in the underlying marine community (Leitão, 2015; Shannon *et al.,* 2014). At monthly resolution, harmonized richness increased from 24.92 ± 0.79 taxa/month in 2023 to 35.33 ± 3.31 taxa/month in 2024. All 12 calendar-month comparisons showed higher richness in 2024 (paired Wilcoxon $W = 0$, $p = 0.000488$). The annual Jaccard dissimilarity index between the standardized 2023 and 2024 species pools reached 0.623, whereas the corresponding Sørensen dissimilarity measured at 0.452. These values indicate that only 23 of the 61 taxa recorded across both years were shared (37.7% similarity), whereas 9 were recorded only in 2023 and 29 only in 2024; because Sørensen weights shared taxa twice, it indicates that shared taxa made up 54.8%

of the average annual species pool. Turnover accounted for approximately 62 percent (%) of Sørensen beta diversity (βSIM = 0.281), whereas nestedness accounted for approximately 38% (βSNE = 0.171), indicating that the temporal contrast involved substantial replacement of landed taxa rather than simple accumulation. Operationally, species turnover denotes the substitution of the nine taxa documented exclusively in 2023 with an equivalent number of taxa unique to 2024, whereas nestedness accounts for the remaining 20 taxa by which the 2024 taxonomic pool exceeded that of 2023. Comparable fisheries-based studies have demonstrated that modifications in landed assemblages frequently reflect expansion or spatial redistribution of fishing effort, targeted shifts in exploited taxa, and alterations in fishing grounds, rather than unambiguous enhancements in ecosystem-level biodiversity (Durante *et al.,* 2020). At genus level, annual richness was 30, 30, 24, and 33 for 2021–2024, respectively, indicating that part of the species-level increase in 2024 reflects finer species resolution within genera. Nevertheless, the 2023–2024 contrast remained robust: monthly genus richness increased from 20.25 ± 0.87 to 26.83 ± 2.29 (higher in all 12 months; W = 0, p = 0.000488), turnover accounted for 62.5% of Sørensen dissimilarity, and the PERMANOVA year effect remained significant (pseudo-F(1,11) = 105.94, p = 0.000488). Excluding the seven single-occurrence taxa likewise did not alter the main patterns (monthly richness higher in all 12 months; Jaccard = 0.574; turnover = 69.9%; pseudo-F(1,11) = 55.32, p = 0.000488). For context, annual Jaccard dissimilarity among 2021–2023 (0.268–0.419) was lower than between 2024 and each earlier year (0.619–0.646), although these single-year contrasts cannot define the range of normal interannual variability. Temporal variability also increased descriptively. Mean Jaccard dissimilarity between consecutive months rose from 0.098 in 2023 to 0.185 in 2024. However, the paired comparison was marginal at the conventional 0.05 threshold (p = 0.054). Accordingly, the empirical data corroborate a discernible elevation in observed monthly richness alongside annual compositional turnover yet yield more ambiguous support for a concurrent intensification of short-term, month-to-month instability. Because richness and compositional turnover capture distinct facets of biodiversity dynamics, they may exhibit differential sensitivities to variation in sampling design, taxonomic granularity, and exploitation patterns (Gotelli and Colwell, 2001).

Multivariate restructuring of landed-fish assemblages

PCoA based on Jaccard distances showed a pronounced separation of monthly assemblages between 2023 and 2024 (Fig. 2). The first two axes represented 84.2% of the variation associated with positive eigenvalues, with PCoA1 accounting for 69.7% and PCoA2 for 14.5%. PCoA1 represented the between-year contrast, driven mainly by taxa recorded in only one year, whereas PCoA2 reflected a shift between January–June and July–December 2023 that was not repeated in 2024. Monthly samples from successive year occupied distinct regions of the ordination space, reflecting a pervasive divergence in assemblage structure rather than a shift constrained to a limited subset of months. Every monthly sample from 2023 exhibited positive PCoA1 scores, whereas all 2024 monthly assemblages yielded negative scores. Furthermore, Jaccard dissimilarity between corresponding months ranged from 0.500 to 0.638, substantially exceeding the mean within-year dissimilarities of 0.224 2(023) and 0.212 (2024); confirming that the observed ordination separation was not driven by any isolated temporal outlier. Ordination-based representations are particularly useful for evaluating temporal community change because trajectories and separation in multivariate resemblance space can reveal changes in assemblage composition that are not captured by univariate diversity measures alone (De Cáceres *et al.,* 2018).

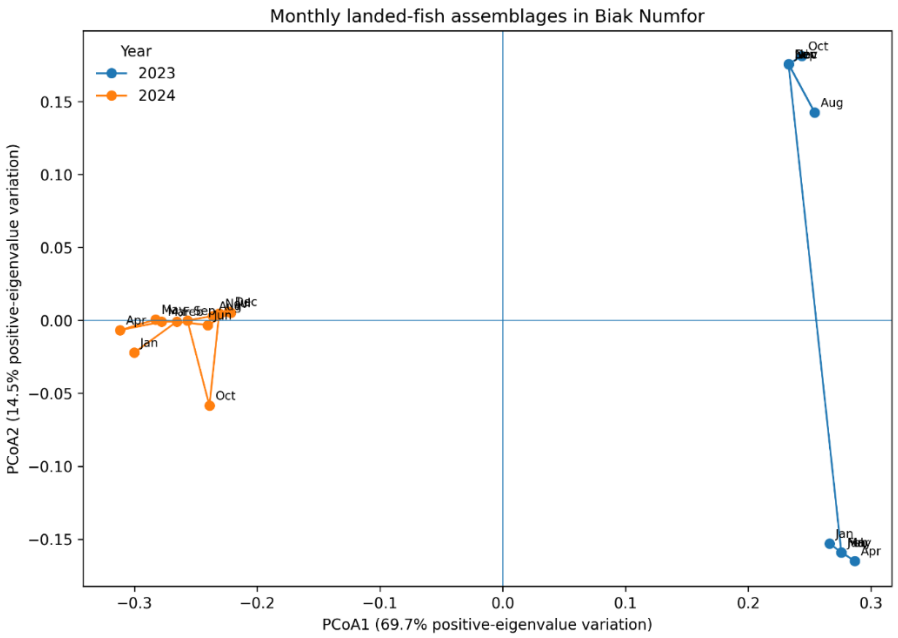

Fig. 2: PCoA of monthly landed-fish assemblages in Biak Numfor in 2023 and 2024 using Jaccard dissimilarity on harmonized presence–absence data. Labels indicate calendar months and lines connect consecutive months within each year

PERMANOVA, with calendar month controlled through paired year-label permutations, indicated a significant year-associated difference in landed assemblage structure (pseudo-F(1,11) = 51.35, p = 0.000488, partial R^2 = 0.824) (Table 1). Because partial R^2 excludes variation attributable to calendar month and was derived from only 12 paired months, this metric reflects the magnitude of the annual contrast relative to residual within-month variation rather than the proportion of total assemblage variation explained by year. Nevertheless, multivariate dispersion also differed between years (PERMDISP F(1,22) = 7.34, p = 0.000488), with mean distance to the group centroid decreasing from 0.187 in 2023 to 0.148 in 2024. This indicates that monthly assemblages were more homogeneous in 2024, consistent with the absence of the within-year shift observed along PCoA2 in 2023. Assessing multivariate dispersion is crucial when interpreting distance-based variations among assemblages, as differences in within-group variance can independently influence apparent multivariate separation (Gijbels and Omelka, 2013). Consequently, the PERMANOVA result should not be interpreted as a pure shift in group centroids: the observed year contrast reflects both compositional location and differences in within-year dispersion. Nonetheless, the magnitude of the dispersion discrepancy remained minor relative to the robust between-year ordination separation: monthly assemblages from 2023 and 2024 exhibited complete non-overlap along the PCoA1 axis, and pairwise dissimilarities between corresponding months consistently surpassed baseline within-year values, confirming that the temporal effect was not predominantly artifactual to differences in multivariate dispersion.

Fishing-gear structure as a major correlate of assemblage composition

Fishing gear was the dominant measured correlate of species composition when the analysis was restricted to five gear categories

Table 1: Multivariate tests of year and fishing-gear effects on harmonized landed-fish assemblages

Dataset	Test	Pseudo-F	df	p	Partial R^2
Monthly assemblage	PERMANOVA: Year | Month	51.35	1,11	0.000488	0.824
Monthly assemblage	PERMDISP: Year	7.34	1,22	0.000488	
Common-gear assemblage	PERMANOVA: Gear | Year + Month	66.40	4,103	0.000500	0.721
Common-gear assemblage	PERMANOVA: Year | Gear + Month	11.88	1,103	0.000500	0.103
Common-gear assemblage	PERMDISP: Gear	51.88	4,115	0.000500	

recorded in both years: fixed gillnet, handline, trap, trolling line, and small pelagic purse seine (Fig. 3). After controlling for year and month, gear explained a large fraction of multivariate variation (pseudo-F(4,103) = 66.40, p = 0.0005; partial R^2 = 0.721; unique total R^2 = 0.687). This strong gear effect is ecologically plausible because different fishing gears selectively capture different combinations of species and functional traits, thereby producing distinct catch assemblages even within the same fishery (Mbaru *et al.,* 2020). These compositional differences were not paralleled by an escalation in sampling effort during 2024. All five common gears were recorded in every month of both years, yet fishing trips declined for each gear (fixed gillnet, 2,835 to 1,932; handline, 2,895 to 2,747; trap, 1,440 to 1,020; trolling line, 2,730 to 2,520; small pelagic purse seine, 466 to 164), reducing total trips from 10,366 to 8,383. Landing records increased from 436 to 910, mainly because of the addition of tuna longline (222 records; 50 trips) and large pelagic purse seine (63 records; 23 trips; 10 months) and the finer disaggregation of 2024 records by vessel class and landing site. A diminished yet statistically significant annual effect persisted subsequent to controlling for fishing gear and calendar month (pseudo-F(1,103) = 11.88, p = 0.0005; partial R^2 = 0.103; unique total R^2 = 0.031). This indicates that gear restructuring accounts for much of the organization of landed assemblages but does not fully account for the 2023–2024 compositional shift. The gear-specific ordination reinforced this result. Although ordination centroids for the common gear types shifted between 2023 and 2024, the magnitude and trajectory of movement varied among gear categories, indicating that the temporal transition was not characterized by a uniform displacement across all fisheries. PERMDISP for gear was also significant (F(4,115) = 51.88, p = 0.0005), demonstrating substantial differences in within-gear heterogeneity. Accordingly, gear-related PERMANOVA results are interpreted as differences in multivariate assemblage structure rather than exclusively as centroid separation. Each ordination centroid depicted in Fig. 3 is derived from 12 monthly assemblages per gear type and annual interval. Within-gear multivariate dispersion decreased declined between 2023 and 2024 for fixed gillnets and traps, increased for handlines and trolling lines, and remained stable for small pelagic purse seines. Consequently, the observed contrasts for gillnets and traps partly reflect heightened structural homogeneity within 2024 assemblages, whereas the contrast for small pelagic purse seines is predominantly driven by a directional shift in centroid coordinates.

Gear-specific comparisons revealed several distinct patterns. Mean richness associated with fixed gillnets was unchanged at 9.50 taxa/month in both years, yet composition differed significantly (pseudo-F(1,11) = 47.50, p = 0.000488; partial R^2 = 0.812). Handline richness increased from 8.50 to 10.17 taxa/month and showed a smaller but significant compositional shift (pseudo-F(1,11) = 5.09, p = 0.0156, partial R^2 = 0.316). Trap richness declined slightly from 7.17 to 6.50 taxa/month while composition changed significantly (pseudo-F(1,11) = 10.63, p = 0.000977, partial R^2 = 0.491). Trolling-line richness decreased from 5.83 to 3.83 taxa/month and differed significantly in composition (pseudo-F(1,11) = 61.22, p = 0.000488, partial R^2 = 0.848). The most pronounced contrast emerged within

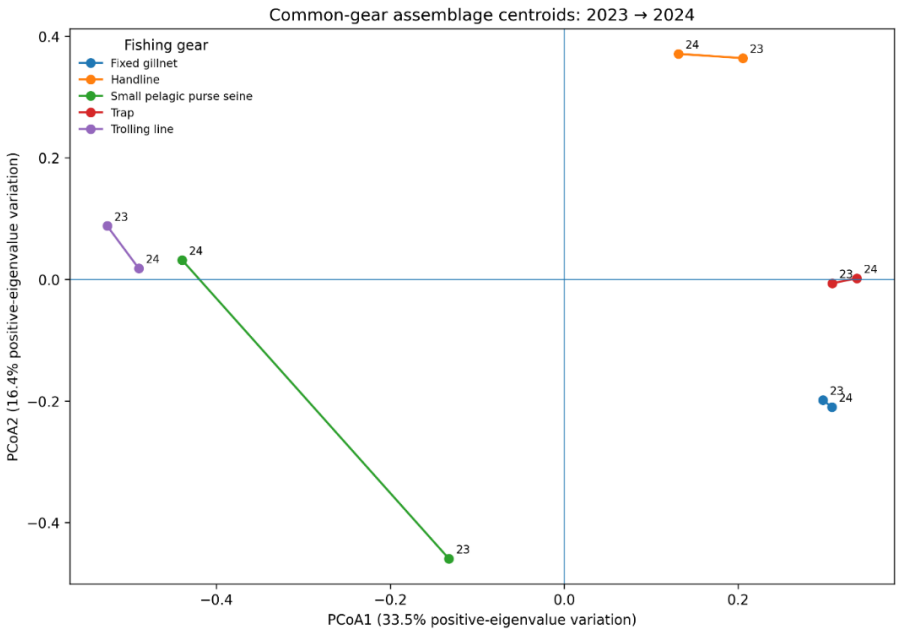

Fig. 3: PCoA centroid trajectories of monthly landed-fish assemblages for fishing gears recorded in both 2023 and 2024. Each line connects the 2023 and 2024 centroid for the same gear; labels 23 and 24 denote year; n = 12 monthly assemblages per gear and year

small pelagic purse seine: mean monthly richness escalated from 3.17 to 7.42 taxa, and paired-month Jaccard dissimilarity reached 1.000, denoting a complete absence of shared harmonized taxa between corresponding monthly assemblages under the current classification (pseudo-F(1,11) = 57.11, p = 0.000488, partial R^2 = 0.838). These contrasting gear-specific responses illustrate why changes in species richness and changes in catch composition should be evaluated separately. Fishing gears types can vary substantially in the species compositions, size spectra, and functional groups they target, whereas disparities in community structure among gears frequently remain pronounced despite comparable patterns in species richness (Fauconnet *et al.,* 2015). Importantly, when the analysis was restricted to the five gears shared between years, mean monthly richness was identical in 2023 and 2024 (24.92 taxa/month in both years), even though multivariate assemblage structure remained significantly different. Annually, these gear types yielded an identical richness of 32 taxa, yet only 22 were shared between years, demonstrating that numerical parity masked the complete turnover of nearly one-third of the taxonomic composition. This outcome decouples two distinct processes that might otherwise be confounded: the overarching elevation in observed richness was primarily associated with an expansion of the gear portfolio, whereas substantial taxonomic turnover also transpired within fisheries represented across both annual periods. Landing location had a comparable influence. When the analysis was restricted to non-port landings, the only landing category recorded in both years, annual richness decreased from 32 to 23 taxa, monthly richness was lower in all 12 months of 2024 (W = 0, p = 0.000488), and dissimilarity was mainly nestedness-resultant (Jaccard = 0.333; turnover = 21.7%), although composition still differed (pseudo-F(1,11) = 35.60, p = 0.000488). The 2024 increase in richness and turnover was therefore associated mainly with landings at PP. Fandoi during the sampling period overall, reflecting temporal variations in species composition and landing patterns.

Indicator taxa and species gains associated with the 2024 assemblage

Indicator-value analysis identified 15 taxa significantly associated with year after Benjamini–Hochberg correction (Fig. 4). Because IndVal was computed from presence–absence data, indicator status reflects consistency of occurrence across months rather than catch dominance. Under the monthly presence–absence framework, exactly three taxa served as perfect indicators for 2023: *Ablennes hians*, *Rastrelliger faughni*, and *Siganus canaliculatus* (IndVal = 1.00; q = 0.00396 for each). Six taxa were perfect indicators of 2024: *Decapterus russelli*, *Istiophorus platypterus*, *Makaira nigricans*, *Siganus corallinus*, *Thunnus alalunga*, and *Xiphias gladius* (IndVal = 1.00; q = 0.00396). Additional 2024 indicators included Parastromateus niger (IndVal = 0.957), *Coryphaena hippurus* (0.926), *Carcharhinus amblyrhynchoides* (0.913), *Cubiceps capensis* (0.913), *Decapterus macrosoma* (0.913), and *Euthynnus affinis* (0.816), all remaining significant after false-discovery-rate adjustment. Indicator species analysis stratified by fishing gear revealed 35 statistically significant gear-associated taxa following correction for multiple-testing, further underscoring the pronounced selectivity characterizing the landed assemblage. Examples included *Epinephelus bleekeri* associated with handline, *Siganus puellus* with fixed gillnet, *Lobotes surinamensis* with trap, and *Auxis thazard* and *Thunnus tonggol* with trolling line. These associations provide a biological explanation for the large multivariate gear effect: changes in the representation of gear types can directly alter which taxa enter the observed landing assemblage. Most taxa added in 2024 were associated with gears first recorded in that year. Of 29 taxa present in the harmonized 2024 pool but absent from the 2023 pool, 28 were recorded in tuna-longline and/or large-pelagic-purse-seine assemblages, and 19 were recorded exclusively in these two gear categories. Because these gears types were documented exclusively in 2024, their contribution is confounded with annual effect and cannot be isolated from broader inter-annual variations; consequently, this association remains strictly descriptive in nature. Within 2024, these taxa accounted for 25.9% of the landed weight, mainly Decapterus spp. and Euthynnus affinis, indicating that they were not merely incidental records. Consequently, these taxa are more accurately construed as an expansion or structural reorganization of the observed landed-species portfolio rather than as definitive evidence of ecological colonization.

Modernization-period change is better characterized as assemblage restructuring than a simple biodiversity increase

The central result is not simply that more taxa were recorded in 2024. Instead, the modernization Instead aligned with a comprehensive restructuring of the landed fish community, integrating an expanded observed species pool, elevated annual beta diversity, considerable taxonomic turnover, and pronounced multivariate separation relative to 2023. An increase in landed-species richness cannot be translated directly into an increase in marine biodiversity. The turnover–nestedness decomposition supports this interpretation: more than half of the Sørensen dissimilarity was attributable to turnover, indicating replacement of landed taxa rather than only the addition of taxa to an otherwise stable species pool. The subset analysis restricted to common fishing gear types revealed a parallel pattern: when data were limited to gears operating in both years, the apparent rise in monthly richness dissipated, whereas the multivariate compositional difference remained statistically significant.

Gear restructuring provides a plausible mechanism for the observed change

The very large gear effect, together with the concentration of 2024-only taxa in tuna longline and large pelagic purse seine, suggests that fishing-practice restructuring may be a key mechanism linking the modernization period to

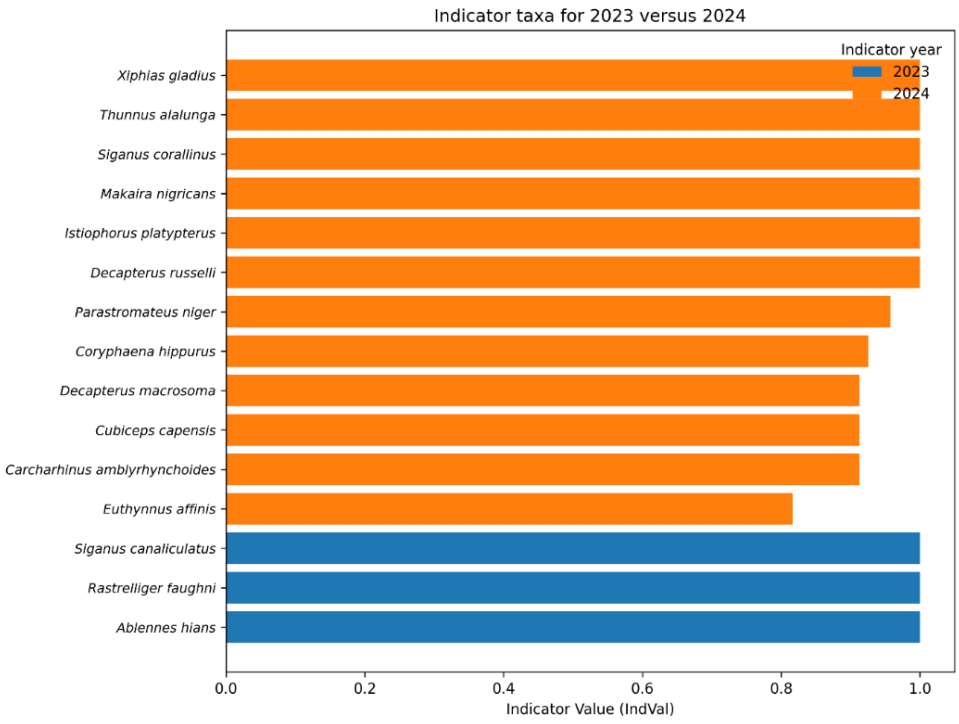

Fig. 4: Significant indicator taxa for 2023 and 2024 based on binary Indicator Value (IndVal). Significance was assessed using exact paired permutations within calendar month and Benjamini–Hochberg correction; only taxa with $q < 0.05$ are shown

the observed landing assemblage. Distinct fishing gears target disparate components of the fish community and operate across varying habitats, bathymetric depths, and grounds. This finding cautions against attributing the full 2023–2024 shift directly to infrastructure modernization: the statistical evidence supports a strong association between gear structure and assemblage composition, while the causal pathway from modernization to changes in gear deployment is not directly observed in the current files. At the same time, gear composition does not explain the entire temporal signal. The persistence of a significant year effect after controlling for fishing gear and calendar month indicates that additional ecological or operational processes contributed to the observed assemblage restructuring. Possible explanations within the scope of the dataset include changes in fishing grounds or vessel operations, altered targeting strategies, seasonal or interannual availability, landing allocation, and changes in reporting resolution. Deployment within the five common gears was also not identical between years. Small pelagic purse seines were operated from vessels below 10 GT in 2023 but from 20–500 GT vessels landing at PP. Fandoi in 2024, including some trips to WPPNRI 712 and 718, which is consistent with their complete monthly turnover; some 2024 handline records also came from 100–200 GT vessels. Conversely, fixed gillnets, traps, and trolling lines were deployed from outboard-motor vessels across both annual periods yet continued to exhibit significant compositional divergence, indicating that variations within comparable fishing configurations also contributed. Consequently, these underlying mechanisms must be treated as working hypotheses pending the acquisition of more granular operational or spatial fisheries data, including vessel-level records, fishing effort estimates, gear-specific information, and detailed catch composition assessments.

Indicator taxa reveal a shift toward a different landed-species portfolio

The indicator analysis provides taxon-level evidence for the compositional transition. The 2024 indicator set included large pelagic taxa such as *Istiophorus platypterus*, *Makaira nigricans*, *Thunnus alalunga*, and *Xiphias gladius*, alongside other pelagic and coastal taxa. Given that the majority of apparent 2024 gains were concentrated within the newly represented tuna-longline and large-pelagic-purse-seine categories, these indicators patterns align closely with an expansion of the operational fishing and landing domain captured by the monitoring program. Five of the six perfect 2024 indicators were landed only at PP. Fandoi by tuna longlines, purse seines, or large-vessel handlines, whereas the 2023 perfect indicators were taken by small-vessel purse seines and fixed gillnets, linking the indicator shift to changes in fleet and landing site rather than habitat availability. The gear-specific indicator results further show that assemblage differences are not arbitrary. Taxa exhibited consistent associations with specific fishing methods, corroborating the inference that shifts in the relative abundance or representation of gear categories can significantly restructure the aggregate landed assemblage. For management, this means that species-level monitoring should be interpreted jointly with gear composition. A port can exhibit higher landed-species richness without necessarily indicating improved ecological condition if the increase arises because the fishing system accesses a broader range of habitats, fishing grounds, or target groups. The importance of integrating environmental performance and sustainability considerations into broader system-level assessments has also been highlighted in other sectors (Cepriadi *et al.,* 2026). Similarly, balancing ecological stability with economic growth under oceanographic variability and coastal interventions is recognized as an important consideration in fisheries systems (Sakti *et al.,* 2026), , particularly for ensuring long-term resource sustainability and livelihood security.

Implications for assessing fishing-village modernization

When evaluating fishing-village modernization, these findings advocate for a conceptual transition away from a simplistic before–after diversity paradigm and toward an integrated assemblage-and-fishing-system framework. Modernization may alter where and how catches are landed, which fleets or gears use the landing facility, and the range of taxa entering the recorded landing system. Consequently, the outcomes of modernization should not be evaluated through species richness alone; rather, a more robust monitoring framework must integrate species occurrence, beta diversity, taxonomic turnover, fishing-gear structure, and the multivariate composition of the landed assemblage. Such an integrated approach is also relevant when assessing temporal and seasonal variability in pelagic fisheries, where changes in fishing activity and operational patterns can influence environmental performance and carbon footprints (Syamdidi *et al.,* 2026). This interpretation also changes how homogenization or differentiation should be evaluated. The 2024 data for PP. Fandoi were clearly differentiated from Biak records without an explicit port assignment, with the observed contrast primarily driven by turnover of landed taxa. Given that landing locations were unrecorded prior to 2024 and specific fishing grounds were undocumented, spatial factors could not be integrated into the primary statistical models; consequently, a portion of the observed temporal contrast is attributable to variations in landing location. A defensible impact evaluation would require explicit identification of treatment and comparison landing sites and consistent port coding before and after modernization. Furthermore, disentangling modernization-associated shifts from the intrinsic interannual variability characteristic of tropical multispecies fisheries necessitates extended temporal monitoring, meaning the observed 2023–2024 contrast may, in part, reflect such natural

background fluctuations. Taken together, the evidence indicates that the modernization period in Biak Numfor was associated with significant differences in the multivariate structure, reflecting both composition and dispersion, of the recorded landed-fish assemblage. The observed elevation in species richness was predominantly attributable to an expanded fishing-gear portfolio; however, compositional replacement of landed taxa persisted even among gears categories common to both years, and a residual year-associated signal remained evident after controlling for gear type and seasonality. Because these patterns are based on presence–absence data, they describe changes in which taxa were landed rather than changes in their catch volume or dominance. The results therefore support interpreting modernization-period change as a reorganization of the fishing and landing system and its associated species portfolio, rather than as evidence of a simple increase or decrease in marine biodiversity.

CONCLUSION

This study demonstrates that transformations associated with fishing-village modernization cannot be adequately assessed through production volumes, economic valuation, or species richness metrics alone. The observed transition in Biak Numfor is more appropriately understood as a restructuring of the fishing and landing system and of the species portfolio represented within it. Fishing gear configurations and landing location emerged as primary structuring determinants of the landed-fish assemblages, while compositional shifts concurrently persisted within specific fishing methods maintained across temporal periods. From a management perspective, this means that changes in landed diversity should be interpreted as signals of changing patterns of resource use rather than automatically as evidence of ecological improvement or degradation. The primary policy implication is that future modernization initiatives must integrate assemblage, and gear-based monitoring criteria from their inception. Investment in landing infrastructure, cold chains, market access, vessel services, or fishing technology can change incentives, fishing reach, gear deployment, and the range of resources entering landing sites. Consequently, monitoring frameworks must transcend conventional indicators to systematically incorporate species occurrence, gear configuration, vessel attributes, available fishing effort, spatial grounds, seasonality, and landing localities. A standardized Port × Month × Gear × Species information architecture would allow managers to distinguish changes arising from fishing-system expansion from changes that may reflect resource availability or ecological condition. These findings also suggest that changes in fishing gear and vessel operations accompanying modernization warrant precautionary monitoring. Modernization policy should therefore avoid treating diversification of landings as an environmental benefit by default. Where new gears or fleet components become prominent, management should assess their selectivity, spatial footprint, target and non-target species, and implications for vulnerable taxa before encouraging further expansion. Environmental safeguards can be reinforced through gear-specific monitoring, regulatory licensing, spatial management, seasonal controls, and the periodic evaluation of assemblage indicators. Such measures would enable modernization initiatives to enhance livelihoods and supply-chain performance while preventing infrastructure development from serving as an indirect conduit for unmanaged increases in fishing pressure. For adaptive management, landed-fish assemblages can function as an operational early-warning layer when interpreted cautiously. Persistent taxonomic turnover among landed species, shifts in indicator taxa, or variations in gear-specific assemblages can pinpoint segments of the fishery warranting

rigorous scrutiny, even when aggregate production volumes remain stable. Such diagnostic signals should prompt targeted evaluation rather than immediate ecological attribution. Where possible, fisheries-dependent monitoring should be complemented by independent information on fishing effort, vessel movements, habitat condition, and fishery-independent ecological surveys. Synthesizing these complementary lines of evidence would empower resource managers to ascertain whether shifts detected at landing sites stem primarily from alterations in fishing behavior, spatial redistribution of effort, market infrastructural forces, or underlying marine ecosystem dynamics. The study further highlights the importance of institutional data governance in environmental management. The inability to reconstruct a consistent port-level before–after comparison illustrates how administrative data design can determine the strength of environmental inference. Modernization programs should therefore treat monitoring infrastructure as part of the intervention itself: standardized digital landing records, harmonized taxonomic reference lists, explicit gear classifications, and traceable spatial identifiers should be established before or at the beginning of infrastructure development. Such an approach would empower subsequent evaluations to transition from retrospective correlation toward robust impact assessment frameworks incorporating credible control sites alongside consistent pre- and post-intervention observations. Overall, the Biak Numfor case suggests that environmentally responsible fisheries modernization requires simultaneous management of infrastructure, fishing practices, and biological monitoring. The critical policy question is not merely whether modernization enhances catch volumes or expands recorded species richness at landing sites, but whether it fundamentally alters how marine resources are accessed and whether those operational shifts remain compatible with sustainable exploitation and ecosystem stewardship. Integrating assemblage-based indicators and gear-sensitive monitoring within modernization programs would provide resource managers with a framework for tracking shifts in resource utilization, evaluating trade-offs between economic development and conservation, and adapting management strategies as the fishery evolves. This approach would strengthen evidence-based decision-making, improve stakeholder participation, and support adaptive fisheries governance under changing ecological and socioeconomic conditions. In this framework, modernization becomes not only an infrastructure or livelihood agenda, but also an opportunity to strengthen evidence-based fisheries governance and integrate environmental safeguards into coastal community development while ensuring long-term ecological and socioeconomic sustainability.

AUTHOR CONTRIBUTIONS

W.I. Sakti conceptualized the study, conducted the analysis, and drafted the manuscript. I.M. Radjawane supervised the research and critically revised the manuscript. H. Latief supervised the research and provided critical scientific thinking in the interpretation of the results. I. Meilano reviewed the analytical approach and results. Prihatiningsih contributed fisheries expertise and species-composition interpretation. M. Dwirastina supported taxonomic harmonization. S.N. Aida contributed to temporal assemblage interpretation. K. Fatah provided expertise on fishing gears. A.A. Utama supported data validation. Husnah contributed to ecological interpretation. A. Suman contributed to fisheries-management interpretation. S. Kaban contributed to the interpretation of fishery resource-utilization patterns. P. Lestari contributed to policy implications. T. Noegroho contributed to the interpretation of fishing operations. T. Hidayat contributed to fisheries-policy and environmental-monitoring implications. M. Zaidan contributed to data analysis. All authors reviewed and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

$****$	Set difference; used in $G_{2024} = S_{2024} \setminus S_{2023}$
a	Number of taxa shared by assemblages A and B
b	Number of taxa occurring only in assemblage A
c	Number of taxa occurring only in assemblage B
i	Sampling-unit, calendar-month, observation, or hypothesis-rank index depending on context
$\times$	Cross-classification or combination of analytical factors, e.g., Year × Month × Gear
Σ	Summation operator
$\surd$	Square-root operator
$\pm$	Plus or minus; used to report mean ± standard deviation
%	Percent
/Month	Per month
α	Statistical significance level
βJAC	Jaccard beta-diversity dissimilarity
βSOR	Sørensen beta-diversity dissimilarity
βSIM	Simpson turnover component of Sørensen beta diversity
βSNE	Nestedness-resultant component of Sørensen beta diversity
λ_k	Eigenvalue of principal coordinate axis k

Λ	Diagonal matrix of eigenvalues
A	Assemblage A in pairwise beta-diversity comparison
A_jg	Specificity component of Indicator Value for taxon j in group g
ANOVA	Analysis of Variance
ASFIS	Aquatic Sciences and Fisheries Information System
B	Assemblage B in pairwise beta-diversity comparison; also the doubly centered matrix in PCoA
B_jg	Fidelity component of Indicator Value for taxon j in group g
C_g	Centroid of group g in multivariate distance space
D	Matrix of pairwise Jaccard distances
D^2	Element-wise squared-distance matrix
d_i	Paired richness difference for calendar month i
df	Degrees of freedom
df term	Degrees of freedom associated with the focal model term
df residual	Residual degrees of freedom
F	F statistic
Fdisp	F statistic for multivariate dispersion
Fobs	Observed pseudo-F statistic
F_r	Pseudo-F statistic obtained under permutation r
FAO	Food and Agriculture Organization of the United Nations
G_{2024}	Set of apparent species gains in 2024 relative to 2023
g	Group index
H	Centering matrix used in PCoA
I	Identity matrix; also used as an indicator function depending on context
I(·)	Indicator function
I_n	n × n identity matrix
IndVal	Indicator Value
$IndVal_jg$	Indicator Value of taxon j for group g
j	Taxon index
k	Ordination-axis or rank index, depending on context
KNMP	Kampung Nelayan Merah Putih
ln(S)	Natural logarithm of species richness
m	Number of hypotheses in multiple-testing correction; also, an eigenvalue index in PCoA
min(b,c)	Minimum of the numbers of taxa unique to assemblages A and B
MSbetween	Mean square among groups
MSwithin	Mean square within groups
n	Number of observations or sampling units
N_g	Number of sampling units in group g
n_jg	Number of sampling units in group g containing taxon j
Nperm	Number of permutations evaluated
p	Statistical probability or p-value
p(i)	Ordered p-value of hypothesis at rank i
$\bar{p}_jg$	Proportion of sampling units in group g in which taxon j occurs
P	Total number of harmonized taxa in the community matrix
PCoA	Principal Coordinates Analysis
PCoA1	First Principal Coordinate axis
PCoA2	Second Principal Coordinate axis
PERMANOVA	Permutational Multivariate Analysis of Variance
PERMDISP	Permutational analysis of multivariate dispersions

PP.	*Pelabuhan Perikanan* (Fishing Port)
pseudo-F	Pseudo-F statistics used in PERMANOVA
q	False-discovery-rate-adjusted p-value
q(i)*	Initial Benjamini-Hochberg adjusted value for hypothesis at rank i
q(i)	Monotonic Benjamini-Hochberg adjusted q-value
R_i	Rank of the absolute paired difference $\|d_i\|$ in the Wilcoxon signed-rank test
R^2	Coefficient of determination / proportion of variation explained
partial R^2	Partial coefficient of determination for a focal PERMANOVA term
r	Permutation index
S	Species/taxon richness or species set, depending on context
S_i	Observed taxon richness in sampling unit i
S_{2023}	Harmonized species set recorded in 2023
S_{2024}	Harmonized species set recorded in 2024
SSterm	Sum of squares associated with a focal model term
SSresidual	Residual sum of squares
V	Matrix of eigenvectors in PCoA
v_k	Eigenvector corresponding to eigenvalue λ_k
W	Wilcoxon signed-rank test statistic
WoRMS	World Register of Marine Species
WPPNRI	Wilayah Perikanan
x_{ij}	Binary occurrence of taxon j in sampling unit i
x_i	Multivariate observation i
Z_k	PCoA coordinate for axis k
z_i	Distance of observation i to its group centroid

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