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Oceanic environmental variability and fishing effort reallocation in data constrain small-scale fishery

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ABSTRACT

BACKGROUND AND OBJECTIVES: Small-scale fisheries in tropical multi-gear systems are shaped by marine environmental variability and pressure on target stocks. In the Timor Sea, seasonal variation in sea surface temperature and chlorophyll-a influences the spatio-temporal distribution of fishing opportunities, while demersal snapper stocks remain vulnerable to overexploitation. This study evaluated whether oceanographic variability and demersal stock pressure were associated with fishing-effort reallocation, while distinguishing fleet-level restructuring from vessel-level gear switching.

METHODS: Vessel-level landing records from 2014 to 2020 were analyzed for vessels of 30 gross tonnage or less, comprising 3,441 records from 619 vessels. Sea surface temperature and chlorophyll-a data were obtained from satellite products, spatially averaged over the fishing domain, aggregated into monthly means, transformed into anomalies, and matched to landing records. To comprehensively evaluate gear dynamics, a multi-tiered analytical framework comprising compositional testing, multinomial logistic regression models, functional gear groupings, and vessel-level Markovian transition matrices were established. Demersal stock status for Lutjanus malabaricus, Lutjanus sebae, and Pristipomoides multidens was determined via length-based spawning potential ratio estimates.

FINDINGS: Sea surface temperature and chlorophyll-a showed strong seasonal and interannual variability but no long-term trends. Gear composition shifted significantly, with purse seine effort increasing and bottom longline use declining relative to handlines. After controlling for month, vessel size, trip intensity, and environmental anomalies, the multinomial model showed an increasing probability of purse seine use over time. Purse seine deployment was significantly associated with lagged temperature and chlorophyll-a anomalies, indicating that pelagic fishing responded to environmentally mediated opportunities rather than productivity alone. Vessel-level transition analysis revealed a high degree of operational inertia; out of 355 paired vessel-year empirical observations, only 32 instances of gear switching were detected, yielding a nominal transition rate of 9.0 percent. Spawning potential ratio values were below the 40 percent management tapercentassessed species, with *Lutjanus sebae* and *Pristipomoides multidens* below the 20 percent limit reference point.

CONCLUSION: The Timor Sea small-scale fishery is undergoing partial effort reallocation rather than complete gear migration. Purse seine expansion reflects fleet restructuring, indicating adaptation to spatio-temporal environmental variability and demersal stock depletion. Management should prioritize snapper stock rebuilding, pelagic effort monitoring, vessel-level gear tracking, and satellite-based environmental indicators.

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45	9	4

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INTRODUCTION

Small-scale fisheries in tropical seas operate as dynamic social–ecological systems in which multispecies exploitation, diverse fishing gears, heterogeneous fleet structures, and oceanographic variability jointly shape fishing strategies. While deep demersal snapper and grouper fisheries hold substantial economic importance in Indonesia, numerous target stocks face escalating fishing pressure—a vulnerability acutely pronounced among species characterized by long life spans and slow growth rates (Wibisono *et al.,* 2022; Wibisono, 2020). At the same time, the performance of these fisheries may also be affected by marine environmental variability because temperature, productivity, and habitat conditions can influence fish distribution, catchability, and fishing-ground formation (Runcie *et al*., 2019; Khan *et al*., 2024).These challenges are intensified by the limited availability of long-term fisheries data, causing management strategies to rely heavily on biological indicators such as catch composition, fish size structure, and reproductive status. Amid the challenges of managing data-limited marine resources, the length-based spawning potential ratio (LB-SPR) methodology has emerged as a vital benchmark for evaluating stock status and verifying that reproductive output remains above critical biological thresholds (Rincón-Sandoval and López-Rocha, 2024; Kasim *et al.,* 2024). However, biological indicators alone may not fully explain changes in fishing behavior, especially when fishing opportunities are also shaped by environmental variability. Remotely sensed oceanographic data, particularly sea surface temperature (SST) and chlorophyll-a, offer a practical way to add an environmental layer to data-limited fisheries analysis because these variables can be observed consistently across space and time using satellite products (López-Martínez *et al*., 2023; Khan *et al*., 2024). Oceanographic variability directly shifts the spatial and temporal distribution of fisheries resources by modifying thermal habitat, primary productivity, prey availability, and the formation of productive fishing grounds. SST reflects thermal suitability and water-mass dynamics, while chlorophyll-a is commonly used as a proxy for primary productivity and potential pelagic foraging habitat. Such environmental variability across tropical marine ecosystems serves as a key driver of fleet adaptation, impacting baseline catch rates while shifting the comparative advantages of demersal- and pelagic-oriented fishing operations (Runcie *et al*., 2019; McInnes *et al*., 2017; Putri *et al*., 2024). In multi-gear fisheries, declining availability of target demersal resources may encourage fishers to modify their fishing strategies in response to ecological and economic pressures. Such adaptive responses can include shifting fishing grounds, increasing fishing intensity, diversifying target species, or reallocating effort toward alternative gears and more productive pelagic resources (Silas *et al.,* 2020; Wiyono *et al.,* 2006). Gear reallocation can be interpreted as a response to two interacting pressures: the declining viability of demersal fishing amid stock depletion, and the expanding opportunities for pelagic fishing driven by favorable oceanographic conditions. However, changes in fleet-level gear composition do not necessarily indicate that individual vessels are actively switching fishing gears. Fishers' decisions are often constrained by financial capital, operational experience, seasonal variability, market access, licensing arrangements, and household dependence on specific fisheries (Andrews *et al.,* 2020; Daw *et al.,* 2012). This distinction underscores the critical analytical nuance required to differentiate between macro-level fleet reconfigurations and discrete, vessel-level gear transitions. Effort displacement from demersal to pelagic fisheries may potentially reduce pressure on depleted snapper stocks, but it can also transfer fishing pressure toward other ecosystems and fishery resources (Nomura *et al.,* 2021; Yletyinen *et al.,* 2018). Previous studies have examined grouper-snapper stock status, small-

scale gear complexity, adaptive fishing behavior, and oceanographic effects on catch dynamics, but these components are often analyzed separately. Extensive empirical literature from Indonesia underscores the inherent socio-ecological complexity of grouper-snapper complexes, emphasizing that data-limited demersal fisheries require high-granularity, gear-specific monitoring alongside spatial and precautionary management frameworks (Herdiana *et al*., 2023; Nadiarti *et al*., 2021; Wibisono *et al*., 2021). However, few studies have integrated vessel-level landing records, gear-use transition analysis, demersal stock-status indicators, and remotely sensed oceanographic variables to evaluate whether fishing-effort reallocation reflects environmental opportunity, biological stock pressure, or broader fleet restructuring. Oceanographic variability, particularly SST and chlorophyll-a anomalies, contributed to changes in fishing strategy by altering the relative attractiveness of demersal- and pelagic-oriented fishing. Specifically, positive chlorophyll-a anomalies are expected to be associated with increased purse seine activity because higher surface productivity may improve pelagic fishing opportunities, while low spawning potential ratio (SPR) values for demersal snapper stocks may indicate biological pressure that reinforces partial effort reallocation away from demersal-associated gears. Consistent with broader literature, this hypothesis posits that environmental fluctuations dictate the spatial and temporal availability of marine resources, which in turn drives tactical adjustments in small-scale fishing behavior to accommodate changing catch viability (Runcie *et al*., 2019; Khan *et al*., 2024; Saldaña *et al*., 2017). This study examines small-scale snapper fisheries operating in the Timor Sea, eastern Indonesia, by integrating vessel-level landing records, remotely sensed SST and chlorophyll-a anomalies, multinomial gear-use models, vessel-level transition matrices, and LB-SPR estimates for key demersal snapper species. Through this integrated approach, the study evaluates whether increasing pelagic-oriented fishing reflects environmental opportunity, demersal stock pressure, or broader fleet-level restructuring. The findings offer valuable contributions to adaptive fisheries management by integrating oceanographic variability, fishing-effort displacement, stock recovery objectives, and vessel-level tracking within a single, cohesive framework. This study aims to evaluate whether oceanographic variability and demersal stock pressure are associated with fishing-effort reallocation in a data-limited small-scale fishery of the Timor Sea. The structural objectives of this study seek to bridge oceanographic variability with fleet dynamics through five sequential aims: first, establishing baseline temporal trends for SST and chlorophyll-a; second, mapping chronological and seasonal variations in fishing activity across years (y) and months; third, determining if localized environmental anomalies dictate the probability of targeting demersal or pelagic resources; fourth, isolating true vessel-level behavioral switching from aggregate fleet-wide trends; and finally, evaluating the implications of these dynamics for demersal snapper stock sustainability and proactive risk management. The analysis focuses on small-scale vessels landing in Kupang, eastern Indonesia, and operating in the Arafura and Timor Sea during the period of 2014–2020, while field survey conducted in 2024.

MATERIALS AND METHODS

Study area and data sources

The study was conducted in the Timor Sea, eastern Indonesia, using 2014–2020 landing records from small-scale fisheries operating through the Port of Kupang, East Nusa Tenggara Province (Fig. 1). The multi-species fishery targets a deep demersal snapper and grouper complex, alongside other reef-associated teleosts, which are harvested utilizing a diverse array of fishing gears including handlines, bottom longlines, gillnets, and purse seines. The three major snapper species caught in the Timor Sea were *Lutjanus malabaricus*, *Lutjanus sebae*, and *Pristipomoides multidens*.

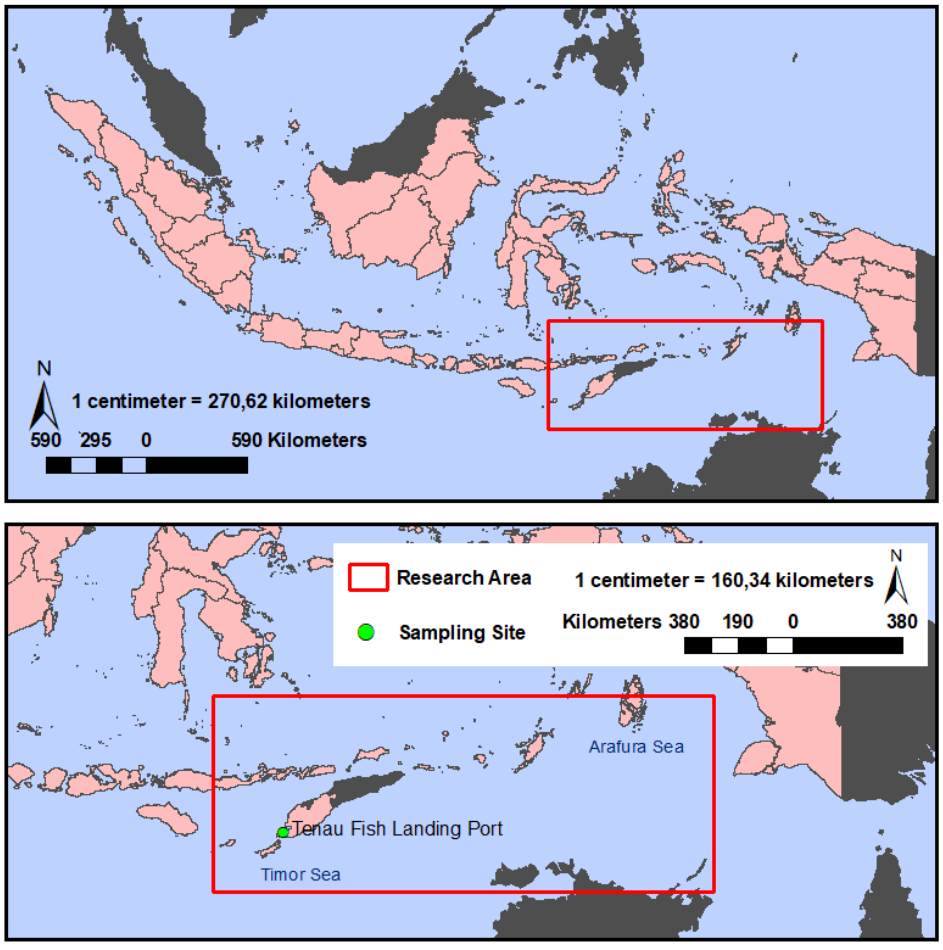


Fig. 1: Geographical location of the study area along with sampling site in the Tenau Landing Port, Kupang, Indonesia

The Timor Sea has strong seasonal and interannual variability driven by southeast and northwest monsoons, regional upwelling, and water-mass exchanges (Peña-Molino *et al.*, 2022). These processes influence SST, nutrient availability, primary productivity, and chlorophyll-a variability. This setting is suitable for examining how environmental variability affects fisheries dynamics and fishing behavior. Fishery-dependent landing records were analyzed to evaluate spatio-temporal gear-use patterns and vessel-level behavioral transitions, while concurrent biological sampling was deployed to assess the reproductive status and gonadal maturation indices of key demersal snapper stocks. Both datasets were integrated to test whether gear changes were consistent with an emerging shift from demersal-targeting gears toward pelagic-oriented gears under declining snapper stock conditions.

Oceanographic data

Oceanographic variables were used as environmental predictors of gear use. SST data were taken from the Copernicus Marine Service Global Ocean OSTIA Sea surface temperature Level 4 product, which provides daily sea surface foundation temperature at 0.05° × 0.05° resolution in NetCDF-4 format. Chlorophyll-a concentration was taken from the Copernicus-glob-color global ocean color bio-geo-chemical

Level 4 product, using the mass concentration of chlorophyll-a in seawater at 4 × 4 kilometer (km) spatial and daily temporal resolution. Both environmental variables were delineated according to the spatial extent of the Timor Sea fishing domain, column- or spatially averaged, and subjected to monthly temporal aggregation before being coupled with fishery landing records by corresponding year and month. Chlorophyll-a was log-transformed to reduce skewness. Monthly anomalies were calculated by subtracting the long-term monthly mean from each observation, and one-month lagged anomalies were used to represent delayed environmental effects on fishing activity. These environmental covariates were integrated into predictive gear-choice frameworks to quantify the specific influence of oceanographic variability on operational transitions between demersal-associated and pelagic-oriented gears.

Gear classification and functional grouping

Landing records were standardized before analysis. Vessel names, registration marks, fishing gear names, and port names were harmonized by removing redundant spaces, correcting inconsistent capitalization, and standardizing spelling variants. To ensure accurate tracking, individual vessels were defined and tracked based on a composite metric of registration mark, vessel name, and gross tonnage. Records were restricted to vessels of ≤30 gross tonnage (GT) for the main small-scale fisheries analysis. Fishing gears were grouped into six analytical categories: handline, pole-and-line, gillnet/net, purse seine, bottom longline, and others. Handline and bottom longline were treated as demersal-associated gears because they commonly target snapper and other demersal species, whereas purse seine was interpreted as a pelagic-oriented gear. This categorization scheme served to evaluate whether the fleet exhibited a systematic transition away from demersal-targeting and toward pelagic-oriented fishing strategies.

Environmental drivers of gear use

Gear composition was summarized annually and monthly using both vessel counts and trip counts. For each period t, the proportional contribution of gear *g* was calculated using Eq. 1 (Zhu and Fang, 2016):

$$P_{g.t} = \frac{N_{g,y}}{\sum_{g=1}^{G} N_{g,t}} \quad (1)$$

Where: $p_{g,t}$ is the proportion of gear g in period t, $N_{g,t}$ is either the number of vessels or number of trips using gear (g), and G is the total number of gear categories. To evaluate whether the distributional shifts in gear composition over time were statistically significant, a chi-square test of independence was executed on the temporal (year-by-gear) contingency table. The strength of association was evaluated Cramér's V using Eq. 2 (Okeke, 2009):

$$V = \sqrt{\frac{X^2}{n(k-1)}} \quad (2)$$

Where: χ^2 is the chi-square statistic, n is the total number of observations, and k is the smaller number of rows or columns in the contingency table. A multivariate analysis of gear composition was also performed using permutational multivariate analysis of variance (PERMANOVA) based on Bray–Curtis dissimilarity. Monthly gear composition was represented as a matrix of gear proportions. Bray–Curtis dissimilarity between periods i and j was calculated using Eq. 3 (Anderson, 2017):

$$BC_{i,j} = 1 - \frac{2\sum_{g=1}^{G} \min(x_{ig}, x_{jg})}{\sum_{g=1}^{G} x_{ig} + \sum_{g=1}^{G} x_{jg}} \quad (3)$$

Where: x_{ig} and x_{jg} are the proportions or counts of gear (g) in periods i and j. PERMANOVA was then used to test the effects of year and month using Eq. 4 (Anderson, 2001):

$$D_{ij} \sim Year + Month \quad (4)$$

Where: D_{ij} is the Bray–Curtis dissimilarity matrix. Year represented long-term temporal change, while month was included to account for seasonal variation. A multinomial logistic regression model was utilized to assess temporal changes in gear-choice probabilities while controlling vessel specifications, operational characteristics, and environmental influences. The response variable was fishing gear category, with handline used as the reference gear because it was the dominant gear in the dataset. The model was specified using Eq. 5 (Runcie *et al*., 2019)

$$Gear_i \sim Year_i + Month_i + GT_i + Trips_i + SST\ anomaly_i + Chl-a\ anomaly_i \quad (5)$$

or, in probability form using Eq. 6 (Hosmer *et al*., 2013):

$$\Pr(Gear_i = g) = \frac{\exp(\beta_{0g} + \beta_{1g}Year_i + \beta_{2g} + Month_i + \beta_{3g}GT_i + \beta_{4g}Trips + \beta_{5g}SST\ anomaly + \beta_{6g}Chl\text{-}a\ anomaly)}{1 + \sum_{n=1}^{G-1}\exp(\beta_{0h} + \beta_{1h}Year + \beta_{2h}Month_i + \beta_{3h}GT_i + \beta_{4h}Trips_i + \beta_{5h}SST\ anomaly + \beta_{6h}Chl\text{-}a\ anomaly)} \quad (6)$$

Where: $\Pr(Gear_i = g)$ is the probability that record i used gear g, $Year_i$ is the year of landing, $Month_i$ accounts for seasonality, GT_i is vessel size, $Trips_i$ is the number of trips, SST $anomaly_i$ and Chlorophyll-a anomaly is differences between the actual value and the normal or climatological value in the same month. Model results were interpreted using relative risk ratios, using Eq. 7 (Long and Freese, 2014)

$$RRR = e^{\beta} \quad (7)$$

A relative risk ratio greater than 1 indicates an increasing likelihood of using a given gear relative to handline, whereas a value below 1 indicates a decreasing likelihood.

Vessel-level gear transition analysis

To distinguish aggregate fleet restructuring from actual fisher- or vessel-level gear switching, a transition analysis was conducted. Annual gear dominance was operationalized at the individual vessel level based on maximum trip frequency; in instances of equal trip distribution, the gear associated with the highest aggregate record volume served as the procedural tiebreaker. Only vessels observed in two consecutive years were included in the transition analysis. The probability of transitioning from gear (g) in year (t) to gear (h) in year $t+1$ was calculated using Eq. 8 (Norris, 1997):

$$P_{gh} = \Pr(Gear_{t+1} = h \mid Gear_t = g \quad (8)$$

Where: P_{gh} is the transition probability from gear g to gear h. Diagonal elements of the transition matrix represent gear persistence, while off-diagonal elements represent gear switching. The overall migration rate was calculated using Eq. 9 (Meyer and Krumme, 2021):

$$MigrationRate = \frac{N_{switch}}{N_{paired}} \quad (9)$$

Where: N_{switch} is the number of vessel-year pairs that changed to dominant gear between consecutive years, and N_{paired} is the total number of consecutive vessel-year pairs. To evaluate whether gear-switching behaviors exhibited directional preference or adhered to a symmetric distribution, Bowker's test of symmetry was executed on the square transition matrix using Eq. 10 (Agresti, 2013):

$$X^2 = \sum_{i<j} \frac{(n_{ij} - n_{ji})^2}{n_{ij} + n_{ji}} \quad (10)$$

Where: n_{ij} is the number of vessels moving from gear i to gear j, and n_{ji} is the number moving in the opposite direction. A significant result indicates that gear switching is directional rather than random or symmetric.

Demersal stock status assessment

Length-frequency and biological data were used to estimate population parameters for *L.*

malabaricus, *L. sebae*, and *P. multidens*. Growth was described using the von Bertalanffy growth function as Eq. 11 (Hordyk *et al*., 2015):

$$L_t = L_\infty\,(1 - e^{-K(t-t_0)}) \quad (11)$$

Where: L_t is fish length at age t, L_∞ is asymptotic length, K is the growth coefficient, and t_0 is the theoretical age at zero length. Total mortality Z was estimated from length-based methods, and fishing mortality F was obtained using Eq. 12 (Hordyk *et al*., 2015):

$$Z = F + M \quad (12)$$

Where: M is natural mortality. The ratio F/M was used as an indicator of fishing pressure relative to natural mortality. Size at first maturity was estimated using a logistic maturity model as Eq. 13 (Hordyk *et al*., 2015):

$$P(L) = \frac{1}{1+ e^{-r(L-L_{50})}} \quad (13)$$

Where: $P(L)$ is the probability that an individual of length $L$is mature, $r$is the slope of the maturity curve, and L_{50} is the length at which 50 Percent (%) of individuals are mature. In the LB-SPR framework, the maturity curve can also be expressed using Eq. 14 (Hordyk *et al*., 2015):

$$P\,(L) = \frac{1}{1+ e^{-(\frac{\ln(19)(L-L_{50})}{L_{95}-L_{50}})}} \quad (14)$$

Where: $L_{95}$is the length at which 95% of individuals are mature. Length at first capture was estimated using a logistic selectivity curve Eq. 15 (Hordyk *et al*., 2015):

$$S\,(L) = \frac{1}{1+ e^{-(\frac{\ln(19)(L-SL_{50})}{SL_{95}-SL_{50}})}} \quad (15)$$

Where: $S(L)$ is the probability of capture at length L, SL_{50} is the length at 50% selectivity, and SL_{95} is the length at 95% selectivity.

Length-based spawning potential ratio

Stock status was assessed using length-based spawning potential ratio. SPR measures the remaining reproductive potential of an exploited population relative to an unfished population Eq. 16 (Hordyk *et al*., 2015):

$$SPR = \frac{SSB_{fished}}{SSB_{unfished}} \quad (16)$$

Where: SSB_{fished} is spawning biomass under fishing and $SSB_{unfished}$ is spawning biomass in the absence of fishing. In the LB-SPR model, SPR was estimated from length composition, maturity, growth, and selectivity parameters. The simplified length-based formulation was, using 17 (Hordyk *et al*., 2015):

$$SPR = \frac{\sum(1-L_x)^{[(\frac{M}{K})(\frac{F}{M})+1]}L_x^b}{\sum(1-L_x)^{[\frac{M}{K}]}L_x^b} \quad (17)$$

Where: L_x is relative length, M/K is the ratio of natural mortality to growth, F/M is the relative fishing mortality, and $b$is the length–weight exponent. SPR values were interpreted using commonly applied reference points: 20% as a limit reference point and 40% as a target reference point. Stock status benchmarks were demarcated such that values below 20% served as evidence of a highly depleted or overfished state; conversely, values spanning the 20% to 40% interval indicated a stock positioned below the target reference point yet remaining above the critical limit threshold. The fisheries, oceanographic, and stock-status datasets were interpreted within an integrated social–ecological framework. Oceanographic variability, represented by SST and chlorophyll-a, was evaluated as a potential driver of changes in fishing opportunity and gear-use patterns. Increasing use of purse seine was interpreted as evidence of a greater contribution of pelagic-oriented fishing activity, whereas changes in the relative importance of handline and bottom longline were examined in relation to both

environmental variability and broader fleet dynamics. Rather than integrating the LB-SPR stock-status indicators as direct explanatory covariates within the behavioral gear-selection models, they were utilized as an exogenous baseline to contextualize the ecological condition of key demersal snapper stocks throughout the study period. Vessel-level transition rates were incorporated to distinguish actual gear switching by individual vessels from aggregate changes in fleet composition, thereby avoiding overinterpretation of fleet-level trends as widespread fisher-level adaptation. By deploying this integrated analytical framework, the study was able to simultaneously quantify four interconnected processes: environmental variability, changes in gear-use probability, fleet restructuring, and the ecological condition of demersal stocks, providing an integrated framework for assessing environmental and fisheries management risks in the Timor Sea.

RESULTS AND DISCUSSION

Oceanographic Variability and productivity patterns

Based on monthly observations from 2014 to 2020 (Fig. 2), the study area showed pronounced seasonal oceanographic variability without significant long-term trends. SST ranged from approximately 26.1 to 31.1 degrees Celsius (°C), with warmer conditions during the Northwest Monsoon (November–April), cooler conditions during the Southeast Monsoon (June–September), and minima generally around August–September. This empirical trend aligns precisely with the monsoon-driven hydrodynamic regimes and localized seasonal upwelling characteristic of eastern Indonesian marine systems, where sustained southeast monsoon winds induce surface cooling and subsequent nutrient enrichment (Peña-Molino *et al*., 2022; Kämpf, 2015; Yu *et al*., 2024). Annual SST increased only slightly, with a slope of 0.0398 °C/y, and the trend was not statistically significant ($p = 0.6141$; $R^2 = 0.055$), indicating seasonal and interannual rather than sustained warming signals during 2014–2020. Monthly chlorophyll-a ranged from approximately 0.18 to 0.55 milligrams per cubic meter (mg/m³), with recurrent peaks of 0.45–0.55 mg/m³ and lower values of 0.18–0.25 mg/m³. Annual mean chlorophyll-a showed only a weak increasing tendency, with a slope of 0.0051 mg/m³/y, which was likewise not statistically significant ($p = 0.3746$; $R^2 = 0.160$). Consequently, surface productivity did not exhibit a sustained, long-term secular trend across the study period; instead, it was governed by oscillatory seasonal dynamics driven by shifting ambient environmental conditions.

Compared with surrounding regions, chlorophyll-a in the study area indicates relatively productive surface waters for eastern Indonesian seas. Handoko *et al*. (2024) reported average chlorophyll-a of approximately 0.09–0.45 mg/ m³ across the Banda Sea, Flores Sea, Timor Sea, and Arafura Sea, with seasonal increases during the Southeast Monsoon. Observed chlorophyll-a concentrations frequently localized between 0.45 and 0.55 mg/m³, aligning with or marginally exceeding the upper threshold of the offshore baseline; nevertheless, these values remained significantly below those recorded in highly productive zones of the Arafura Sea, where coupled shelf and upwelling mechanisms sustain concentrations of several mg/m³ (Yu *et al*., 2024). These patterns are linked to the regional monsoon system. During the Southeast Monsoon, stronger winds enhance upwelling in eastern Indonesia, including the Arafura Sea, southern Java–Timor corridor, and parts of the Lesser Sunda region. Previous studies show that Arafura Sea upwelling intensifies during this period, lowering SST and elevating chlorophyll-a (Kämpf, 2015; Yu *et al*., 2024). However, upwelling effects in the study area are unlikely to be uniform; they should be strongest in exposed coastal and shelf environments, while broader fishing grounds

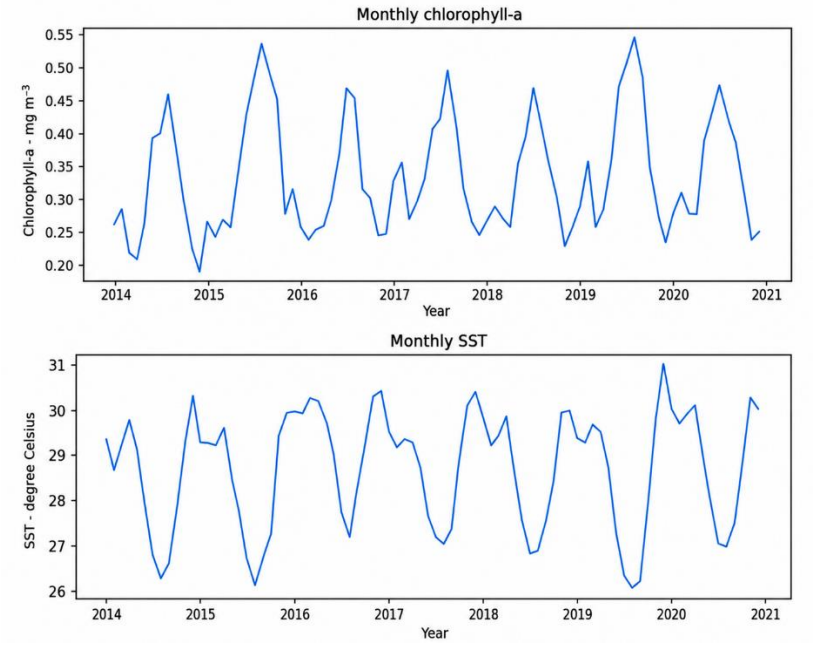


Fig. 2: Monthly mean for SST and Chlorophyill-a from 2014–2020

reflect monsoonal forcing, circulation, water-mass exchange, and interannual variability. Overall, oceanographic conditions in the Timor Sea exhibited marked variabilityat seasonal and interannual scales but lacked a statistically significant secular trajectory over the 2014–2020 study period. SST and chlorophyll-a displayed seasonal cycles, alternating anomalies, and periodic productivity increases. Thus, purse seine increases during specific periods should be interpreted not only as responses to demersal stock pressure, but also as responses to environmental opportunities created by SST and chlorophyll-a variability.

Temporal changes in fishing activity and gear composition

The landing-record dataset contained 3,575 vessel landing records from 646 unique vessels. After restriction to small-scale vessels of ≤30 GT, the analytical dataset comprised 3,441 records from 619 vessels. Six standardized gear categories were identified: handline, pole-and-line, gillnet/net, purse seine, bottom longline, and others. Handline emerged as the predominant gear type within the fishery, constituting 1,513 records. The remaining effort was distributed in descending order of frequency among pole-and-line with 617 records, gillnet/net with 480 records, purse seine with 354 records, bottom longline with miscellaneous gears accounting for the final 289 records, and others with 188 records. The temporal pattern, as indicated in Fig. 3, showed a marked restructuring of the fleet, with handline and purse seine becoming increasingly prominent in later years, while bottom longline declined in relative importance and pole-and-line lost its early dominance. The expanding footprint of purse seine operations alongside the concomitant decline in bottom longline usage points to a progressive fleet restructuring from demersal to pelagic-targeted efforts, unfolding against a baseline of marked variability in SST and chlorophyll-a concentrations. Annual landing records increased from 210 in 2014 to 641 in 2018, 1,059 in 2019, and 1,071 in 2020, indicating expansion in recorded activity, reporting intensity, or vessel participation after 2018.

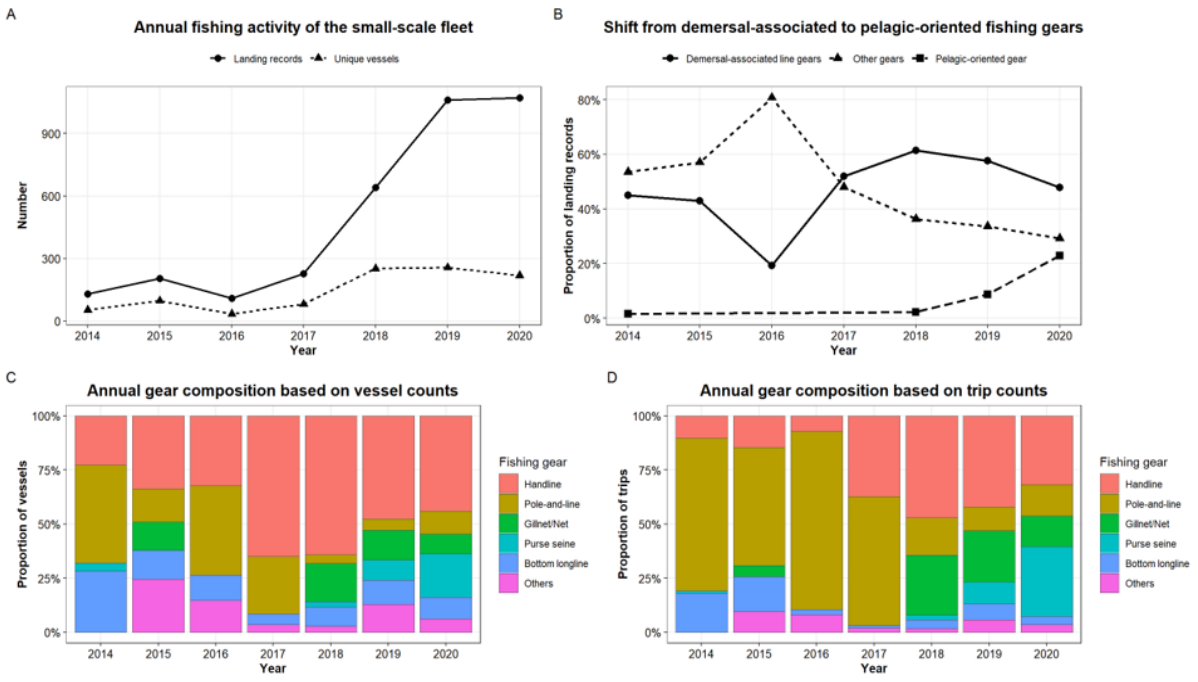


Fig. 3: Temporal dynamics of fishing activity and fishing gear composition in the small-scale fleet landing at Kupang from 2014 to 2020. Panel A shows annual landing records and unique vessels. Panel B shows the relative contribution of demersal-associated line gears, pelagic-oriented gear, and other gears. Panel C shows annual gear composition based on vessel counts, while Panel D shows gear composition based on trip counts.

This increase was uneven across gears. In 2014, the small-scale fleet was dominated by pole-and-line: 45.3% of vessels, followed by bottom longline (28.3%), handline (22.6%), and purse seine (3.8%). Based on trip counts, pole-and-line represented 70.8% of trips, bottom longline 18.1%, handline 10.2%, and purse seine less than 1%, showing strong early dominance of line-based demersal strategies. Later years showed a clearer shift. Handline records increased from 22 in 2014 to 457 in 2020, and purse seine from 2 to 246 records. Bottom longline fishing operations exhibited fluctuations without significant expansion, whereas the pole-and-line sector maintained a persistent yet diminished presence. Consequently, the small-scale fleet transitioned from an early reliance on demersal-associated line gears toward a more diversified structure characterized by increased purse seine representation. This pattern indicates potential reallocation toward pelagic-oriented opportunities under variable SST and chlorophyll-a conditions. The chi-square test confirmed a highly significant year–gear association ($\chi^2 = 1171.5$; 30 degrees of freedom; $p < 2.2 \times 10^{-16}$). Cramér's V was 0.261, indicating a moderate but meaningful association. The PERMANOVA based on Bray–Curtis dissimilarity revealed that interannual variance accounted for 55.7% of the total variation in monthly gear composition and was highly significant. Conversely, seasonal effects (month) explained a negligible 6.6% of the variance and lacked statistical significance. These findings indicate that structural changes within the fishery were primarily driven by interannual dynamics rather than seasonal fluctuations, reflecting a broader macro-level reorganization between 2014 and 2020.

Oceanographic drivers of gear use

The environmental multinomial logistic regression model elucidated the temporal

dynamics of gear utilization and its relationship to oceanographic variability. Handline was the reference category because it dominated the dataset. The full environmental model improved fit relative to the null model (Table 1), confirming that temporal, operational, and oceanographic predictors explain a significant proportion of the variation in gear choice. Relative to handline, purse seine had the strongest positive temporal trend (Table 2), with a year coefficient of 1.343 and a relative risk ratio (RRR) of 3.829. This indicates that, even after controlling season, vessel size, trip intensity, and oceanographic predictors, the relative likelihood of purse seine use increased markedly over the study period. In contrast, bottom longline showed a significant negative temporal trend relative to handline reference category (-0.387 and an RRR of 0.679), denoting a progressive decline over the study period. Gillnet/n*et al*so showed a positive temporal trend, although the increase was much weaker than that observed for purse seine. Pole-and-line and the "others" category did not show significant year effects. Overall, these results confirm a structural shift within the small-scale fleet, characterized by an increase in purse seine use and a concomitant decline in bottom longlines. This pattern reflects a strategic reallocation of effort from demersal to pelagic fisheries. The addition of oceanographic predictors revealed that gear choice was also environmentally structured. As shown in Table 3 and Fig. 4B, the likelihood of using purse seine relative to handline was significantly associated with both SST anomaly and Chlorophyll-a anomaly. For purse seine, the coefficient for SST anomaly was negative (-0.516; RRR = 0.597; p = 0.013), and the coefficient for log Chlorophyll-a anomaly was also negative (-0.474; RRR = 0.623; p = 0.024). These results indicate that the relative likelihood of purse seine use decreased under higher SST and higher Chlorophyll-a anomalies and conversely increased under relatively cooler and lower-than-average chlorophyll conditions in the previous month. Consequently, the utilization of purse seines appears independent of broad-scale productivity increments, indicating instead a strategic linkage to localized pelagic fishing opportunities that emerge under transitional or non-peak productivity conditions.

This pattern indicates that purse seine use was shaped by pelagic opportunity rather than productivity alone. Although chlorophyll-a indicates productive waters, high chlorophyll does not always coincide with maximum surface catchability of schooling pelagic fish. Pelagic species availability may increase under specific oceanographic conditions, such as the concentration of prey fields, the presence of transitional water masses, or the aggregation of schools along frontal zones following elevated productivity events. The negative association between purse seine use and chlorophyll-a anomaly suggests responses to aggregation opportunities after or around localized productivity pulses, not necessarily during peak chlorophyll. The negative SST anomaly effect also indicates greater purse seine likelihood after cooler conditions, possibly reflecting enhanced mixing, localized upwelling influence, or water-mass changes that improve pelagic habitat and aggregation. Consequently, while purse seine operations expanded over the long term, their monthly deployment patterns remained heavily conditioned by short-term thermal variability. Gear-specific responses differed: gillnet/net had negative associations with both SST and chlorophyll-a anomalies, whereas bottom longline was positively associated with chlorophyll-a anomaly but not SST. Overall, variations in gear deployment patterns mirrored both systemic long-term fleet restructuring and acute, short-term oceanographic fluctuations. Monitoring SST and chlorophyll-a may help anticipate environmentally mediated shifts in fishing behavior, especially purse seine use for pelagic opportunities, thereby supporting adaptive fisheries management and more responsive ecosystem-based resource planning.

Table 1: Model fit comparison for the multinomial logistic regression

Comparison	Likelihood ratio (LR)_statistic	df	p_value	Akaike information criterion (AIC)_null	AIC_full	Delta_AIC
Full model vs null model	3549.79	80	0	10643.09	7253.29	3389.79

Table 2: Gear-specific temporal effects from the multinomial logistic regression model

Gear comparison	Year coefficient	Standard error (SE)	Total mortality (z) value	p value	Relative risk ratio	95% CI	Interpretation
Pole-and-line vs Handline	-0.068	0.057	-1.192	0.233	0.934	0.835-1.045	No significant association
Gillnet/Net vs Handline	0.286	0.076	3.767	0.00016	1.331	1.147-1.544	Increasing relative likelihood over time after controlling for oceanographic predictors
Purse seine vs Handline	1.343	0.178	7.537	4.82E-14	3.829	2.701-5.430	Increasing relative likelihood over time after controlling for oceanographic predictors
Bottom longline vs Handline	-0.387	0.052	-7.429	1.09E-13	0.679	0.613-0.752	Decreasing relative likelihood over time after controlling for oceanographic predictors
Others vs Handline	-0.091	0.068	-1.328	0.184	0.913	0.798-1.044	No significant association

Table 3: Gear-specific oceanographic effects from the environmental multinomial logistic regression model

Gear comparison	Environmental predictor	Year coefficient	Standard error (SE)	z value	p value	Relative risk ratio	95% CI	Interpretation
Pole-and-line vs Handline	SST anomaly	0.201	0.129	1.560	0.119	1.223	0.950-1.574	No significant association with Lagged SST anomaly
Pole-and-line vs Handline	Chlorophyll-a anomaly	0.354	0.134	2.643	0.008	1.425	1.096-1.853	Increasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Gillnet/Net vs Handline	SST anomaly	-0.717	0.128	-5.593	2.23E-08	0.489	0.380-0.628	Decreasing relative likelihood with higher Lagged SST anomaly
Gillnet/Net vs Handline	Chlorophyll-a anomaly	-0.661	0.133	-4.980	6.35E-07	0.517	0.398-0.670	Decreasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Purse seine vs Handline	SST anomaly	-0.516	0.207	-2.488	0.013	0.597	0.398-0.896	Decreasing relative likelihood with higher Lagged SST anomaly
Purse seine vs Handline	Chlorophyll-a anomaly	-0.474	0.210	-2.254	0.024	0.623	0.412-0.940	Decreasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Bottom longline vs Handline	SST anomaly	0.059	0.106	0.558	0.577	1.061	0.862-1.306	No significant association with Lagged SST anomaly
Bottom longline vs Handline	Chlorophyll-a anomaly	0.447	0.114	3.925	8.69E-05	1.563	1.251-1.954	Increasing relative likelihood with higher Lagged log Chlorophyll-a anomaly
Others vs Handline	SST anomaly	0.125	0.135	0.929	0.353	1.133	0.870-1.476	No significant association with Lagged SST anomaly
Others vs Handline	Chlorophyll-a anomaly	0.069	0.143	0.487	0.626	1.072	0.811-1.418	No significant association with Lagged log Chlorophyll-a anomaly

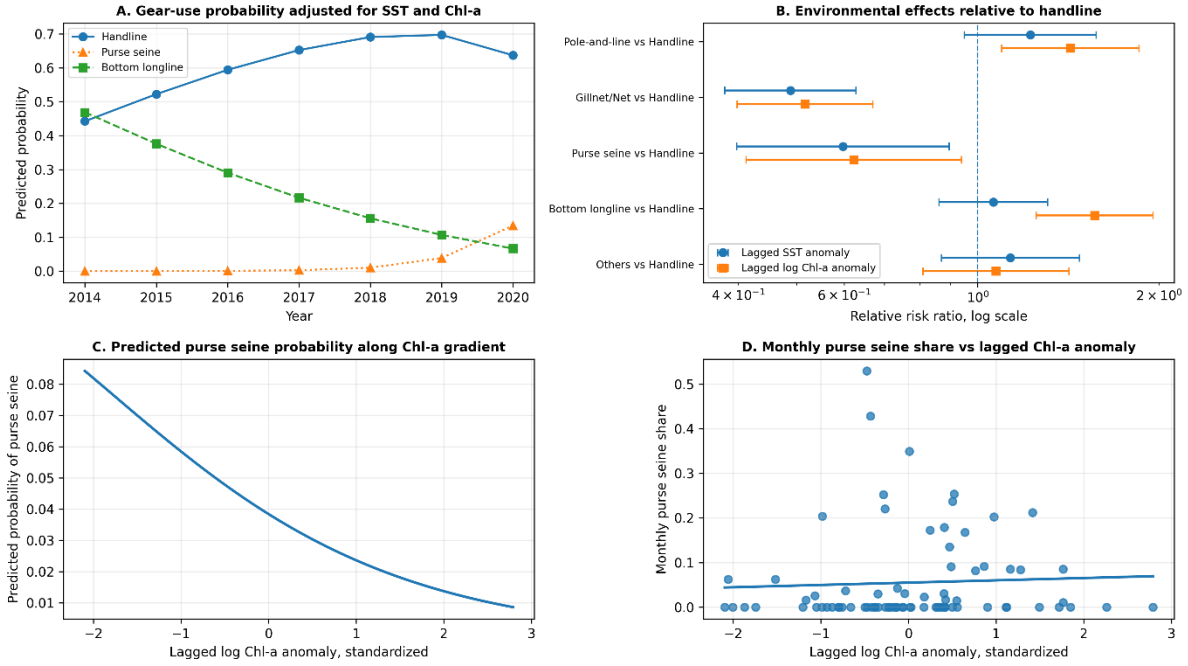


Fig. 4: Gear-specific trends and oceanographic predictors of purse seine expansion in the small-scale fleet

Vessel-level gear transitions and fleet restructuring

Aggregate and model-based analyses showed strong gear-composition changes (Fig. 5), but vessel-level transition analysis showed limited individual gear switching. Among 355 paired vessel-year transitions identified in consecutive observation periods, only 32 involved a shift in dominant gear, indicating a relatively low gear migration rate of 9.0%. Thus, aggregate restructuring should not be interpreted as widespread vessel-level switching. No gear changes occurred in 2014–2015 or 2015–2016. Migration appeared after 2016, with rates of 5.9% in 2016–2017 and 6.1% in 2017–2018. The highest rate occurred in 2018–2019, with 17 of 118 transitions switching gear, or 14.4%, then decreased to 8.2% in 2019–2020. Consequently, the detection of gear-switching behavior became more pronounced during the latter stages of the study period, coinciding with the rapid expansion of both fleet composition and recorded fishing effort. Although aggregate gear composition changed strongly, vessel-level switching was limited and concentrated in directional pathways, especially gillnet/net to purse seine. The transition matrix showed high persistence: pole-and-line had complete persistence, bottom longline 97.3%, purse seine 93.8%, handline 91.5%, gillnet/net 77.1%, and "others" 71.4%. These elevated diagonal values demonstrate that majority of vessels retained their dominant gear type between consecutive years, indicating high operational fidelity. Off-diagonal transitions were structured. The main pathway was gillnet/net to purse seine, with 11 transitions, equal to 22.9% of gillnet/net paired transitions. Other pathways included handline to others, others to handline, handline to bottom longline, bottom longline to handline, and purse seine to gillnet/net. Bowker's test of symmetry was significant (test statistic = 13.6; 4 degrees of freedom; p = 0.0087), showing that switching was directional rather than random or symmetric. Consequently, purse seine growth extends beyond a simple cohort of existing vessels switching gears; rather, it indicates selective

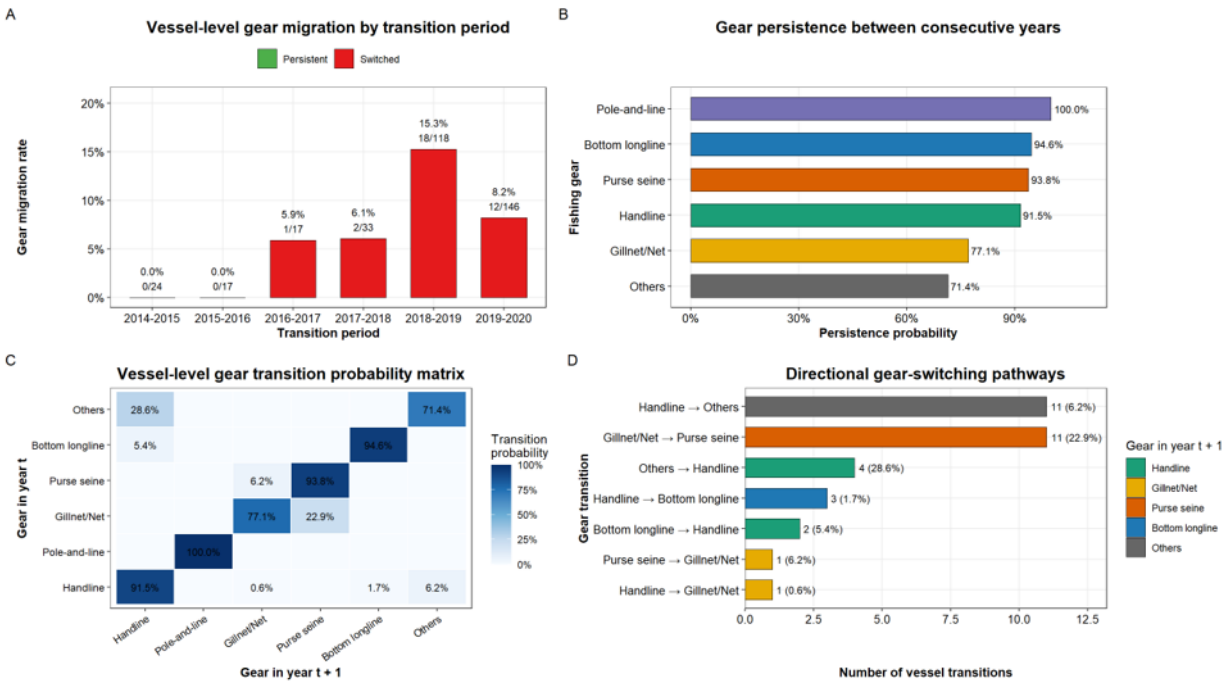


Fig. 5: Vessel-level gear transitions and the scale of gear switching in the small-scale fleet

pelagic-oriented vessels, and systemic shifts in fleet structure. The observed change is best described as fleet-level restructuring with selective vessel-level adaptation rather than mass gear transition.

Functional gear reorientation under environmental variability

The functional gear analysis grouped handline, bottom longline, and gillnet/net as demersal-associated gears, purse seine as a pelagic-oriented gear, and pole-and-line and others as other gears, as described in Fig. 6. This categorization establishes a functional framework for interpreting the oceanographic gear-use model, explicitly demonstrating whether the growing predominance of purse seine operations corresponded to a broader systemic shift in fishing orientation. Across the analytical dataset, demersal-associated gears remained the dominant functional group, accounting for 2,283 landing records, followed by other gears with 804 records and purse seine with 354 records. Annual composition, however, showed substantial variation. The demersal pressure proxy index did not decline steadily across the study period, but instead fluctuated strongly, with higher values in 2018–2019 followed by a decline in 2020. These findings indicate that the fleet maintained a robust reliance on demersal-associated fisheries, despite a concurrent expansion in the relative importance of pelagic-oriented operations during the latter stages of the study period. The clearest functional change was the expansion of purse seine. Its share of landing records increased from 1.6% in 2014 to 8.7% in 2019 and 23.0% in 2020, while its share of trips increased from 0.9% in 2014 to 10.2% in 2019 and 32.3% in 2020. Furthermore, this trend is supported by the multinomial model, wherein a significant temporal increase in purse seine operations relative to handlines was observed after accounting for oceanographic predictors. Notably, the proliferation of purse seine operations did not signify a total displacement of demersal-associated gears. Rather, it reflects a recent, partial and recent functional reorientation,

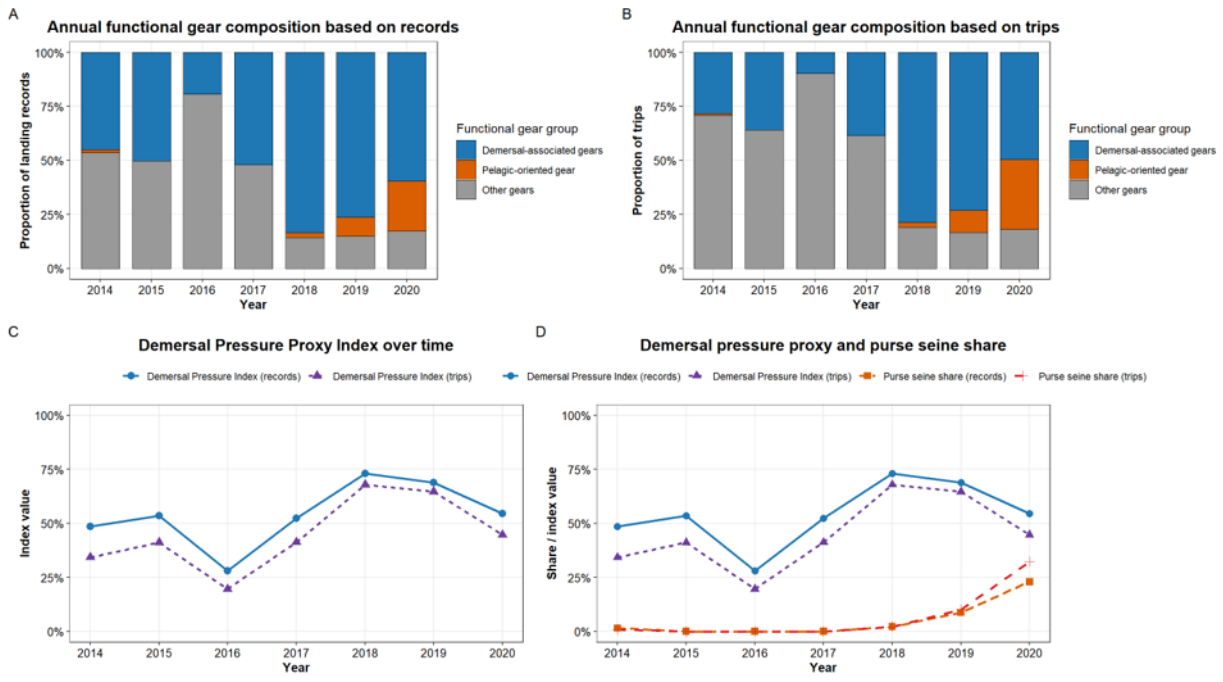


Fig. 6: Functional gear reorientation and demersal pressure context in the small-scale fleet

in which pelagic-oriented fishing expanded concurrently with a sustained reliance on demersal strategies. In the revised environmental framing, this pattern is interpreted as evidence of fishing-effort reallocation under multiple influences. Mechanistically, short-term oceanographic variability creates transient opportunities for pelagic exploitation, while chronic pressure on demersal stocks establishes the broader ecological imperative for fishers to increasingly use alternative gear strategies. Therefore, the Demersal Pressure Index does not indicate a simple transition away from demersal fishing, but it supports a more nuanced interpretation: the fleet remained demersal-linked, yet became increasingly capable of exploiting pelagic opportunities, particularly during 2019–2020. This functional reorientation serves as a critical bridge to the stock-status analysis, given that the persistent reliance on demersal-associated gears coincided with consistently depressed SPR values for key demersal snapper species.

Demersal stock status as ecological context

The biological stock indicators provide ecological context for interpreting gear-use reallocation in the Timor Sea small-scale fleet. While the preceding analyses demonstrate that gear selection co-varied with temporal and oceanographic factors, the corresponding SPR metrics reveal that primary demersal snapper stocks were already experiencing severe exploitation pressure. The three main species assessed were *Lutjanus malabaricus*, *Lutjanus sebae*, and *Pristipomoides multidens*. These species differed in biological characteristics, maturity size, selectivity, and stock status, but all had SPR values below the commonly used 40% management target. For *Lutjanus malabaricus* (Fig. 7), the estimated length at first maturity was 44.5 centimeters (cm), while length at 50% capture was approximately 51 cm. The estimated SPR was 23%, which is slightly above the 20% limit reference point but well below the 40% management target. This indicates that the stock has not yet breached its minimum biological

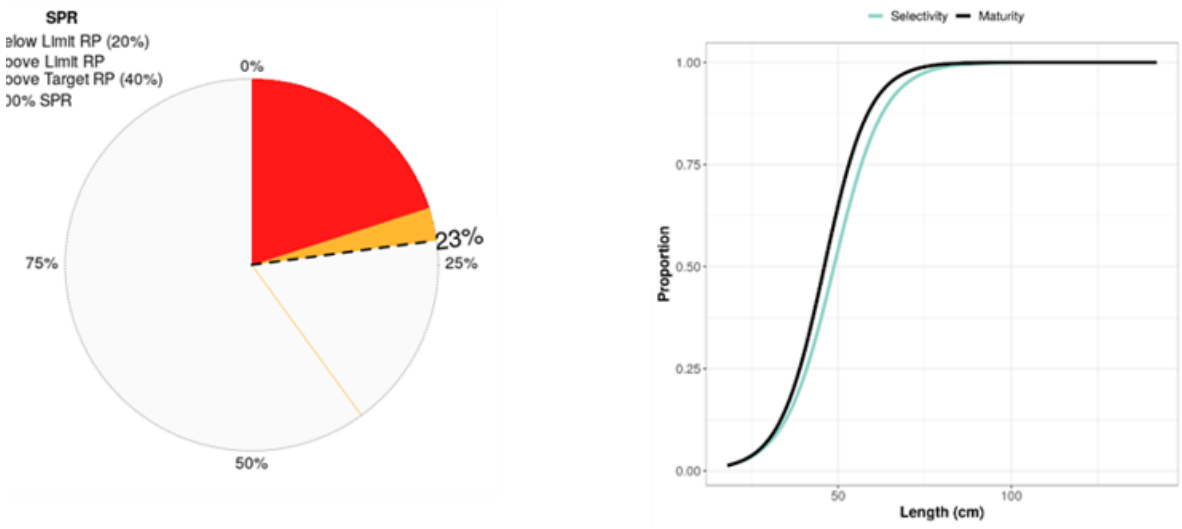


Fig. 7: SPR value, mean length at capture, and length at first maturity of Lutjanus malabaricus

threshold, its overall reproductive potential has been substantially compromised. The estimated fishing mortality to natural mortality ratio (F/M) of 1.81 suggests that fishing mortality exceeds natural mortality, indicating considerable fishing pressure on the stock. Thus, *L. malabaricus* can be interpreted as a stock under stress but not yet in the most critical category. For *Lutjanus sebae* (Fig. 8), the estimated length at first maturity was 46.8 cm and length at 50% capture was approximately 50.5 cm. The estimated SPR was 15%, which is below the 20% limit reference point, confirming a depleted status and a high probability of ongoing overfishing. The F/M ratio was estimated at 2.01, suggesting that fishing pressure is more than twice the level of natural mortality. Given that *L. sebae* is a long-lived and relatively slow-growing species, this low SPR is concerning because recovery may be slow even if management measures are implemented. The most critical condition was observed for *Pristipomoides multidens* (Fig. 9). This species had an estimated length at first maturity of 46.7 cm and length at 50% capture of 47.17 cm, were highly convergent, indicating that individuals were being harvested almost immediately upon reaching reproductive maturity. It is estimated SPR was only 6%, far below the 20% limit reference point and far below the 40% management target. The F/M ratio was 4.88, the highest among the three assessed species, indicating extremely high fishing pressure relative to natural mortality. This result suggests that *P. multidens* is in severely depleted condition and requires urgent management attention. These SPR results show that demersal snapper resources in the Timor Sea were subject to severe biological pressure, a condition that unfolded in parallel with structural modifications to the fleet's gear configurations. Although oceanographic variability may help explain short-term differences in gear-use probability, the low SPR values indicate that demersal fishing occurred against a background of reduced reproductive capacity, particularly for *L. sebae* and *P. multidens*. Thus, these stock-status results do not imply a direct causal link to purse seine growth but instead offer critical ecological context explaining why effort reallocation occurs alongside chronic demersal resource pressure. In this framing, SPR provides the biological backdrop, while SST and chlorophyll-a variability help explain environmentally mediated fishing opportunities and gear-use responses across seasons and changing oceanographic conditions over time.

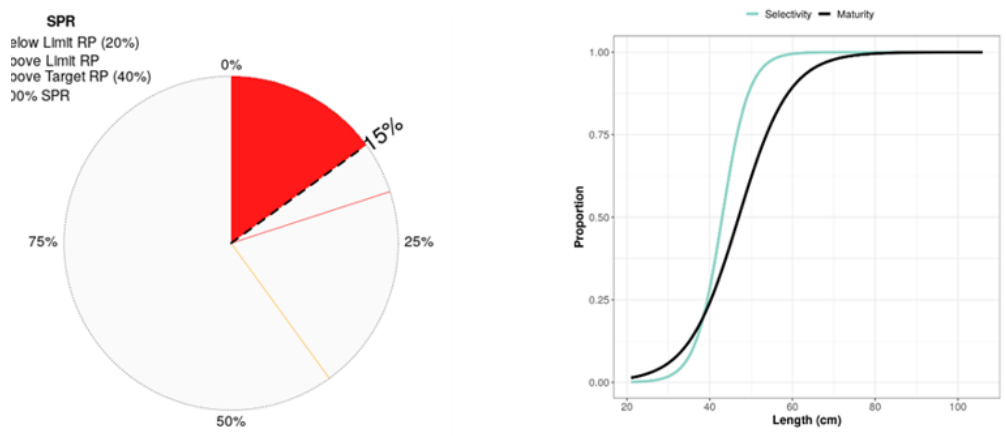


Fig. 8: SPR value, mean length at capture, and length at first maturity of Lutjanus sebae

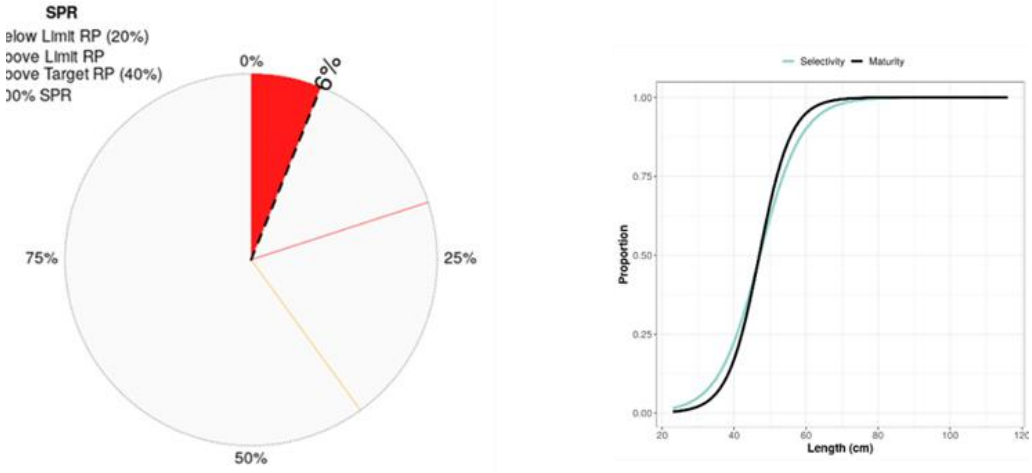


Fig. 9: SPR value, mean length at capture, and length at first maturity of Pristipomoides multidens

Environmental variability, stock pressure, and fishing-effort reallocation

The stock pressure–gear response matrix, detailed in Table 4, integrates three analytical dimensions: oceanographic variability, demersal stock condition, and observed gear-use reallocation. The SPR results showed that the three assessed demersal snapper species exhibited compromised reproductive potential, with empirical SPR values consistently falling below the 40% management target threshold. Two species, Lutjanus sebae and Pristipomoides multidens, were already below the 20% limit reference point, indicating severe biological pressure. These species are mainly associated with handline, bottom longline, and gillnet/net fisheries, which were classified as demersal-associated gears. This biological pressure coincided with a period of pronounced structural shifts in fleet gear composition and Controlling for operational and oceanographic variables, the multinomial regression framework revealed a pronounced temporal trajectory toward purse seine deployment, while bottom

Table 4: Integrated stock pressure and gear response matrix linking demersal snapper stock status with observed fishing gear dynamics in the Timor Sea small-scale fleet

Stock group	Main target gears	SPR evidence	Stock pressure status	Observed gear response	Policy relevance
Lutjanus malabaricus demersal stock	Handline, bottom longline, gillnet/net	SPR = 23%	Below target; moderate–high pressure	Bottom longline declined; handline remained dominant; purse seine increased	Prevent further decline through size limits, stock monitoring, and effort control
Lutjanus sebae demersal stock	Handline, bottom longline, gillnet/net	SPR = 15%	Below limit; overfished risk	Increasing evidence of fleet reorientation toward purse seine	Recovery measures, spawning protection, and monitoring of displaced effort
Pristipomoides multidens demersal stock	Handline, bottom longline, gillnet/net	SPR = 6%	Critically depleted	Selective but directional gear switching; increasing purse seine representation	Priority recovery stock; strict harvest control and possible temporary restrictions
Pelagic resources	Purse seine	Not assessed	Unknown	Strong increase in purse seine uses over time	Pelagic monitoring needed to prevent unmanaged effort displacement
Mixed resources	Pole-and-line, others	Not assessed	Unknown	No consistent temporal trend	Improve species-level reporting and gear-target classification

longline operations significantly contracted relative to the handline baseline. Simultaneously, SST and chlorophyll-a anomalies were significantly correlated with the relative probability of gear choice, demonstrating that short-term environmental fluctuations directly modulate fishing opportunities and operational strategies, consistent with previous findings on the influence of upper-ocean variability on marine ecosystems and fisheries (Jaishree and Ravichandran, 2024). The increase in purse seine fishing should therefore not be interpreted as a direct or fleet-wide replacement for demersal fishing. Vessel-level transition analysis showed that most vessels retained their dominant gear, and only 9.0% of consecutive-year vessel pairs changed gear. This indicates that the observed pattern represents selective adaptation and fleet restructuring rather than widespread individual gear migration. Contextually, the proliferation of purse seine fishing underscores a localized reallocation of harvesting capacity toward pelagic-oriented dynamics; however, this shift did not diminish the continued importance of demersal-associated fisheries. Similar interactions between environmental conditions, fishing activities, and fisheries management have also been recognized within broader socio-environmental and territorial contexts of artisanal fisheries (Díaz-Ponce *et al.,* 2026). This interpretation has important management implications. Rebuilding demersal snapper stocks should be combined with monitoring of displacement and pelagic fishing expansion. Implementing demersal recovery protocols without concurrent tracking of gear utilization risks a hidden reallocation of fishing effort toward alternative, poorly assessed pelagic resources. The matrix therefore supports an adaptive management approach that integrates snapper recovery measures, environmental monitoring, vessel-level gear tracking, and cross-resource fishing pressure assessment.

Implications for environmental and fisheries management

This study indicates that the small-scale fishery operating through the Timor Sea is undergoing partial fishing-effort reallocation within a variable marine environment. The declining relative importance of bottom longline and increasing use of purse seine suggest that fishing activity became more diversified across demersal- and pelagic-oriented strategies. This trend does not imply a total abandonment of demersal fishing, as demersal-associated gears persisted throughout the study period and the Demersal Pressure Index failed to show a continuous monotonic decline. Instead, the results point to selective effort diversification and fleet restructuring, particularly after 2018–2019. The oceanographic results offer

critical contextual frameworks for interpreting the observed structural reconfigurations within the fishery. SST and chlorophyll-a did not show significant long-term trends during 2014–2020, but both variables showed strong seasonal and interannual variability. Such variability can influence fish distribution, habitat suitability, catchability, and fishing-ground formation, thereby affecting the relative attractiveness of different fishing strategies (Runcie *et al*., 2019; McInnes *et al*., 2017). Purse seine expansion reflects not only responses to demersal stock pressure but also favorable environmental conditions. The significant shift in annual gear composition confirms fleet restructuring rather than random variation. Purse seine use increased over time after controlling for month, vessel size, and trip intensity, indicating a genuine change in fleet strategy. However, vessel-level transitions were limited, with only 9.0% of paired vessel-year observations changing dominant gear. This means that aggregate fleet restructuring was not driven by widespread gear switching by individual vessels, but likely by a combination of selective switching, vessel entry, differential activity levels, and changes in reporting intensity. Parallel empirical research in data-limited, small-scale fisheries indicates that fishers frequently adapt by adjusting fishing duration, spatial grounds, depth strata, target species, or operational expenditures, rather than executing complete gear substitutions (Saldaña *et al*., 2017; Frawley *et al*., 2021). Stock-status indicators provide ecological context for these gear-use patterns. The estimated SPR values for *Lutjanus malabaricus*, *Lutjanus sebae*, and *Pristipomoides multidens* were all below the 40% management target, while *L. sebae* and *P. multidens* were below the 20% limit reference point. These results indicate reduced reproductive capacity in key demersal snapper stocks, especially *P. multidens*, which had an SPR of only 6%. Nonetheless, this close temporal alignment—characterized by suppressed SPR thresholds, a contraction in bottom longline operations, and a simultaneous surge in purse seine deployment—warrants a nuanced and cautious interpretation. The evidence indicates that demersal stock pressure, environmental variability, and fleet restructuring are associated, but stock depletion alone did not drive purse seine expansion. Although effort shifted from depleted demersal stocks may reduce snapper fishing pressure, it may increase pressure on pelagic resources, particularly under favorable oceanographic conditions. Without comparable monitoring of pelagic fisheries, emerging sustainability risks may remain undetected until catch rates decline. Ecosystem-based approaches are therefore needed because gear changes can affect target species, bycatch, trophic structure, fishing power, and competition among fishing groups (Herrón *et al*., 2019; Sun *et al*., 2023). For management, policies should operate at two connected levels. First, demersal snapper recovery remains urgent, especially for *L. sebae* and *P. multidens*, through species-specific size limits, protection of spawning areas, seasonal restrictions, and control of fishing mortality. Second, cross-fishery effort displacement toward pelagic frameworks and purse seine deployment warrants systematic monitoring to safeguard against the inadvertent reallocation of ecological risk between resource complexes. These actions should be supported by environmental indicators such as SST and chlorophyll-a anomalies, which may provide early-warning information on changing fishing opportunities and potential shifts in fleet behavior. Adaptive and climate-ready management frameworks emphasize the need for flexible policies that respond to shifting resource availability, environmental variability, and changing fleet behavior (Bell *et al*., 2020; Bastardie *et al*., 2022). The rise of purse seine also has implications for fishing power. Purse seine operations can be more efficient than passive gears, particularly when supported by larger vessels, improved engines, lights, navigation, or fish-finding technology. Consequently, omitting these efficiency gains from effort standardization frameworks may cause nominal effort data to substantially underestimate the true magnitude of contemporary fishing pressure. Management should therefore move beyond gear names alone and consider vessel size, propulsion, gear type,

fishing grounds, species composition, and environmental conditions. Such classifications can better represent fishing power and ecological impact in tropical multi-gear fisheries (Munga *et al*., 2014; Eigaard *et al*., 2014). Additionally, this study highlights the urgent need to improve taxonomic resolution in commercial catch reporting. Purse seine was classified as pelagic-oriented based on gear characteristics, but direct species-composition data from purse seine landings would strengthen interpretation. Participatory or application-based monitoring frameworks possess the capacity to enhance the resolution of catch and effort data while simultaneously fostering direct stakeholder engagement in fisheries management (Porriños *et al*., 2025). For the Timor Sea, such monitoring would be most useful if combined with monthly SST and chlorophyll-a information, allowing managers to evaluate whether changes in catch composition or gear use coincide with environmental anomalies. These outcomes should be interpreted considering several structural limitations. The landing datasets are potentially confounded by shifting reporting fidelity, most notably from 2018 onward. Additionally, the dominant-gear attribution method lacks the granularity to capture high-frequency intra-annual shifts among multi-gear vessels. The biological assessment was restricted exclusively to three demersal snapper species; consequently, the ecological implications for pelagic frameworks subject to escalating purse seine pressure warrant further independent evaluation. In addition, SST and chlorophyll-a are broad environmental indicators and do not capture subsurface temperature, currents, fronts, dissolved oxygen, prey fields, or fine-scale fishing-ground selection. These limitations are common in data-limited fisheries, where incomplete monitoring can obscure true effort, catch composition, stock condition, and fisher response to environmental variability (Gill *et al*., 2017; Dunbar *et al*., 2023). While acknowledging these structural constraints, the synergy of this integrated methodology establishes a more resilient framework for adaptive resource management than traditional, single indicator approaches such as standalone stock or gear analysis. By combining oceanographic indicators, LB-SPR estimates, multinomial gear-use models, and vessel-level transition matrices, this study distinguishes environmental variability, demersal stock condition, aggregate fleet restructuring, and actual vessel-level switching. Overall, the Timor Sea small-scale snapper fishery appears to be undergoing adaptive reorganization rather than a complete transition away from demersal fishing. Consequently, effective management frameworks must synthesize demersal snapper stock rebuilding, pelagic effort monitoring, gear-transition tracking, participatory catch reporting, and satellite-based environmental monitoring to mitigate the risk of serial resource depletion while safeguarding the operational flexibility required by small-scale fishing communities.

CONCLUSION

This study demonstrates that fishing-effort reallocation in the Timor Sea small-scale fishery was shaped by the interaction of oceanographic variability, changing gear-use patterns, fleet restructuring, and persistent demersal stock pressure. SST and chlorophyll-a showed strong seasonal and interannual variability during 2014–2020, providing an important environmental context for interpreting changes in fishing strategies. Paradoxically, despite the absence of significant long-term trend in either variable, their transient anomalies retained a significant association with gear-use probability. This divergence underscores the role of short-term oceanographic variability in modulating contemporary fishing opportunities across distinct gear cohorts. The small-scale fleet showed clear temporal restructuring. Purse seine increased markedly over the study period, while bottom longline declined relative to handline. The environmental multinomial logit model confirmed that the probability of purse seine deployment increased significantly, even after controlling for temporal factors (months), vessel dimensions, trip intensity, and anomalies in both SST and chlorophyll-a. This indicates that the rise of purse

seine reflected a genuine change in gear-use probability rather than only seasonal or operational differences. However, the direction of the environmental effects suggests that purse seine use was not simply driven by higher productivity alone but may have been linked to more specific pelagic fishing opportunities associated with cooler and transitional environmental conditions. Vessel-level transition analysis revealed that macro-level fleet restructuring does not reflect widespread gear substitution by individual fishers. Only 32 of 355 consecutive vessel-year pairs changed to dominant gear, corresponding to a migration rate of 9.0%. Therefore, the observed shift is best described as selective vessel-level adaptation and fleet-level restructuring rather than a complete migration away from demersal fishing. The SPR estimates provide ecological context for interpreting the observed reallocation. All assessed demersal snapper species were below the 40% management target, while *Lutjanus sebae* and *Pristipomoides multidens* were below the 20% limit reference point. Although the data underscores a state of pronounced biological duress among demersal resources, this pressure must not be construed as the sole catalyst underlying regional purse seine proliferation. Overall, the evidence suggests partial fishing-effort reallocation toward pelagic-oriented opportunities under variable oceanographic conditions and continued demersal stock pressure. Management should therefore combine demersal snapper rebuilding, pelagic effort monitoring, vessel-level gear tracking, improved species-level reporting, and satellite-based environmental monitoring to prevent unmanaged displacement of fishing pressure.

AUTHOR CONTRIBUTIONS

K. Kasim contributed to the conceptualization of the study, prepared the initial draft of the manuscript, and conducted the literature review. M.R. Putri supervised the manuscript writing process. S. Nurdjaman provided overall study supervision and contributed to the conceptual development of the draft, while I.A. Fikri offered critical revisions to enhance the quality of the manuscript. T.A. Saputra supported data collection and supervision, and H. Selia contributed to data analysis and interpretation. S. Triharyuni strengthened the references, citations, and analytical components, while B.R.D. Nugraha compiled the field data. All authors reviewed and approved the final manuscript for publication.

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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

%	Percent
°	Degree
°C	Degrees Celsius
°C/y	Degrees Celsius per years
≤	Less than or equal to
×	Multiplication sign
χ^2 / $\chi 2$	Chi-square statistic
AIC	Akaike information criterion
BC	Bray–Curtis dissimilarity
CC BY	Creative Commons Attribution License
CI	Confidence Interval
cm	Centimeter
D_{ij}	Bray–Curtis dissimilarity matrix
Eq	Equation
F	Fishing mortality
F/M	Fishing mortality to natural mortality ratio
g	Gear
G	Total number of gears
GT	Gross tonnage
K	Growth coefficient
km	Kilometer
L	Fish length
L∞	Asymptotic length
L50	Length at 50% maturity
L95	Length at 95% maturity
LB-SPR	Length-Based Spawning Potential Ratio
LR	Likelihood ratio
M	Natural mortality
MMAF	Ministry of Marine Affairs and Fisheries
M/K	Natural mortality to growth coefficient ratio
mg/m³	Milligrams per cubic meter
$N_{g,t}$	Number of vessels or number of trips
N_{paired}	The total number of consecutive vessel-year pairs
N_{switch}	number of vessel-year pairs that changed to dominant gear between consecutive years
ORCID	Open Researcher and Contributor ID
PERMANOVA	Permutational multivariate analysis of variance
P_{gh}	Transition probability from gear g to gear h
Pr	Probability
RRR	Relative risk ratio
SE	Standard error
SL50	Length at 50% selectivity
SL95	Length at 95% selectivity
SPR	Spawning potential ratio
SSB	Spawning stock biomass
SST	Sea surface temperature
WWF	Worldwide Fund for Nature
x_{ig}	The proportions or counts of gear (g) in periods i
x_{jg}	The proportions or counts of gear (g) in periods j
y	Years
Z	Total mortality

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