

Structural Transformation and Value-Based Economic Resilience in Madeira's Fisheries Sector

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Research Article

Keywords: Madeira fisheries, structural transformation, value-based economic resilience, landing-category concentration, value-based adjustment, fisheries specialisation, blue economy

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10853488/v1>

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Additional Declarations: No competing interests reported.

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Abstract

This study examines the long-run structural transformation and value-based economic resilience of Madeira's fisheries sector from 1976 to 2024. Using official annual fisheries statistics, monetary values expressed in constant 2024 euros, landing-category shares, concentration and diversity indices, volatility measures, descriptive time-trend models with Newey–West heteroskedasticity- and autocorrelation-consistent inference, Mann–Kendall and Sen trend tests, Bai–Perron structural-break checks, and an endpoint real-value decomposition, the analysis distinguishes physical contraction from value-based adjustment and increasing specialisation. Total landings fell by 45.2%, from 6,417 tonnes in 1976 to 3,517 tonnes in 2024, whereas real landed value decreased by 6.99%, from €17.98 million to €16.72 million. Aggregate real unit value was 69.7% higher at the 2024 endpoint, but neither the HAC model nor the Mann–Kendall test supports a sustained long-run increase in real unit value; by contrast, real landed value shows a modest negative long-run trend. Concentration increased, and diversity declined in both physical and economic terms. Black scabbardfish was the only category with higher endpoint quantity and real value, and it showed the lowest volatility in quantity and real landed value. In contrast, tuna and similar species remained economically important but comparatively volatile. The evidence therefore supports net physical contraction, partial value-based adjustment, and strong specialisation. Madeira's fisheries became smaller in endpoint terms and more dependent on a narrower set of commercial categories, showing that preservation of a substantial share of real landed value can coexist with reduced portfolio diversification. These findings concern the value dimension of resilience and should not be interpreted as evidence of profitability, fisher welfare, or ecological sustainability.

Keywords: Madeira fisheries; structural transformation; value-based economic resilience; landing-category concentration; value-based adjustment; fisheries specialisation; blue economy.

1. Introduction

Fisheries on small oceanic islands operate under ecological, geographic, and market constraints that differ from those affecting continental fisheries. Limited shelf area, deep surrounding waters, restricted fishing grounds, dependence on a small number of commercially viable resources, and exposure to transport and market bottlenecks can constrain both production and diversification. These features make island fisheries useful settings for examining how fisheries sectors adjust over long periods, when physical output, landed value, species composition, and market conditions do not necessarily move in the same direction.

Madeira is a particularly relevant case. Deep waters, a narrow insular shelf, steep submarine slopes, low-productivity oceanic conditions, and limited demersal habitat shape the archipelago's fisheries. Previous research has characterised Madeira as a high-trophic-level, relatively low-diversity fisheries system, with a strong dependence on black scabbardfish and migratory tuna resources (Iborra Martín, 2008; Hermida & Delgado, 2016). Other components, including small pelagic fisheries, are also important but are affected by environmental sensitivity, seasonal variability, discarding and slipping practices, and changing oceanographic conditions (Tejerina et al., 2019; Vasconcelos et al., 2024). Recent work on the tuna pole-and-line supply chain further highlights constraints related to catch quality, prices, market demand, transport, labour availability, and fleet viability in the Portuguese archipelagos of Madeira and the Azores (Silva et al., 2025).

These characteristics raise an important empirical question. Long-run change in Madeira's fisheries cannot be understood by asking only whether landings increased or declined. A sector may contract in physical terms while retaining part of its economic value through higher unit values, shifts in species composition, or greater reliance on high-value categories. Conversely, nominal landed-value growth may overstate economic performance if inflation is not taken into account. Similarly, increasing dependence on a few commercially important categories may support landed value in the short or medium term while reducing diversification and weakening portfolio-buffering capacity. The central issue is therefore whether Madeira's fisheries experienced physical contraction, value-based adjustment, increasing specialisation, or some combination of these processes.

The existing literature provides important but fragmented evidence. Madeira-specific studies examine ecological constraints, long-run trophic patterns, small-pelagic dynamics, tuna supply-chain limitations, small-scale fishing practices, and species-specific or bycatch-related concerns (e.g., Iborra Martín, 2008; Hermida & Delgado, 2016; Tejerina et al., 2019; Martínez-Escarriaza et al., 2021; Vasconcelos et al., 2024; Freitas et al., 2025; Silva et al., 2025). Broader fisheries research also shows that landed quantities, values, unit values, diversification, and income stability may follow different trajectories and that portfolio effects can reduce variability in catches and fishing income when fisheries are sufficiently diversified (e.g., Albo-Puigserver et al., 2022; Vargas et al., 2022; Eurich et al., 2024; OECD, 2025; European Commission, 2025). However, these dimensions have not previously been integrated into a single long-run assessment of Madeira that jointly evaluates

landings, inflation-adjusted landed value, unit values, species concentration and diversity, volatility, trend evidence, structural breaks, and real-value decomposition.

This study addresses that gap by assessing structural transformation and value-based economic resilience in Madeira's fisheries sector from 1976 to 2024. Structural transformation is defined as long-run change in landed quantity, real landed value, unit values, landing composition, concentration, and diversity. Value-based economic resilience is defined more narrowly as the sector's capacity to preserve part of its real landed value despite lower physical landings through changes in real unit values and landing composition. This definition deliberately isolates the value dimension of resilience and should not be interpreted as evidence of profitability, fisher welfare, ecological sustainability, or general adaptive capacity.

The study asks: how did Madeira's fisheries sector change between 1976 and 2024, and what do these changes reveal about its value-based economic resilience? To answer this question, the analysis uses official annual fisheries statistics for five consistently reported landed categories: black scabbardfish, tuna and similar species, other species, horse mackerel, and mackerel. These are treated as statistical landing categories rather than strictly biological species because some groups combine multiple species. The empirical strategy combines CPI-adjusted monetary values, nominal and real unit values, concentration and diversity indicators, volatility measures, first-last comparisons, subperiod averages, descriptive trend models with Newey–West HAC standard errors, Mann–Kendall and Sen's slope tests, Bai–Perron structural-break checks, and a real-value decomposition.

The study makes three main contributions. First, it distinguishes nominal value growth from real economic adjustment by expressing landed values in constant 2024 euros. Second, it links aggregate change to category-level restructuring, showing how different landed categories contributed to changes in quantity, real value, volatility, concentration, and diversification. Third, it clarifies a resilience–specialisation trade-off in a small oceanic-island fisheries system: preservation of a substantial share of real landed value can coexist with greater dependence on a narrower set of commercially important categories.

Based on the literature and Madeira's fisheries structure, three hypotheses guide the analysis. H1 states that Madeira's fisheries exhibit net physical contraction over the study horizon, reflected in lower 2024 landings and lower post-peak subperiod averages even if the path is not a smooth monotonic decline. H2 states that partial value-based adjustment mitigated physical contraction, such that the decline in real landed value was smaller than the decline in landed quantity and was associated with endpoint real-unit-value and compositional changes, without requiring sustained growth in real landed value or real unit value. H3 states that the sector became more specialised over time, reflected in higher landing-category concentration and lower diversity.

The remainder of the article is organised as follows. **Section 2** reviews the literature on island fisheries, structural change, value-based adjustment, diversification, and resilience. **Section 3** outlines the data and methods. **Section 4** presents the empirical results. **Section 5** discusses the findings in relation to the hypotheses and the wider literature. **Section 6** concludes with policy implications and directions for future research.

2. Literature review

Madeira's fisheries are shaped by geographical, ecological, and economic constraints that may limit fishing opportunities and diversification. Deep waters characterise the archipelago, a narrow insular shelf, steep submarine slopes, low-productivity oligotrophic conditions, and limited demersal habitat. Using aggregated landings data for 1938–2014 and taxonomically detailed records available from 1978 onward, Hermida and Delgado (2016) describe a high-trophic-level fishery dependent on a limited set of resources, particularly black scabbardfish and migratory tunas. Iborra Martín (2008) likewise characterises Madeira's fleet as predominantly small-scale and strongly reliant on passive, line-based gears. Martínez-Escauriaza et al. (2021) compare artisanal and recreational small-scale fisheries in Madeira and document differences in catch composition, catch per unit effort, and fishing pressure on coastal resources. Evidence from the tuna pole-and-line supply chain in the Azores and Madeira further identifies constraints involving catch quality, prices, market demand, transport, labour availability, and fleet viability (Silva et al., 2025).

Long-run fisheries transformation may involve changes in physical output, economic value, and landing composition that do not move in parallel. Disaggregated landing trends are therefore informative because individual resources can follow markedly different trajectories over time (Monteiro, 2026). At the broader international level, OECD (2025) reports that marine capture production declined in volume across the covered countries and territories between 2005 and 2022 while the nominal value of landings increased substantially. These heterogeneous trajectories imply that structural transformation cannot be inferred from aggregate landed quantity alone. Composition and diversification are also relevant because species dependence can shape ecological sensitivity and vulnerability across fleets and regions (Albo-Puigserver et al., 2022).

Economic value provides a distinct perspective on this transformation. Landed quantity, landed value, and unit values may diverge because of prices, landing composition, quality, and market conditions (OECD, 2025; European Commission, 2025). When physical output contracts, preserving part of real landed value through changes in real unit values and landing composition can be interpreted as a value-based adjustment. This is a deliberately narrow construct: it may indicate that part of a physical contraction was absorbed in value terms, but it does not establish profitability, improved welfare, ecological

sustainability, or general adaptive capacity. This distinction aligns with broader resilience research, which identifies ecological, socioeconomic, and governance attributes as jointly relevant to fishery resilience (Eurich et al., 2024).

Diversification may buffer species that respond asynchronously to environmental or market variability. Vargas et al. (2022) show that portfolio effects can reduce variability in aggregate catches and fishing income in a multispecies small-scale fishery. Conversely, dependence on a limited number of species or commercial categories can reduce this buffering potential and increase exposure to category-specific disturbances. Concentration alone, however, does not establish vulnerability because broader resilience also depends on ecological, socioeconomic, market, and governance capacities (Eurich et al., 2024). Mangubhai et al. (2024), for example, identify access to financial services, functioning markets, supporting infrastructure, and disaster-risk management as important dimensions of small-scale fisheries resilience. Accordingly, concentration and diversity are treated here as indicators of structural dependence and potential exposure, not as direct measures of resilience or vulnerability.

Madeira-specific research documents several components of long-run change but generally treats them separately. Tejerina et al. (2019) examine the small-pelagic purse-seine fishery and highlight differences between catches and official landings associated with discarding and slipping. Vasconcelos et al. (2024) show that long-term small-pelagic dynamics are sensitive to environmental variability and warming. Silva et al. (2025) identify market, quality, transport, labour, and fleet constraints in the tuna pole-and-line supply chain, while Freitas et al. (2025) document long-term elasmobranch landings and bycatch-related management concerns in Madeira. Existing studies therefore provide detailed evidence on specific resources, ecological pressures, and value-chain constraints, but an integrated sectoral assessment linking long-run landed quantity to real landed value, real unit values, landing composition, concentration, diversity, and volatility remains limited. The present study addresses that gap for 1976–2024.

3. Materials and methods

3.1. Data and variables

This study uses annual fisheries data for Madeira, Portugal, covering 1976–2024. **Figure 1** presents the study area, the five landed categories analysed (black scabbardfish, tuna and similar species, other species, horse mackerel, and mackerel), and the regional fish-landing infrastructure. The infrastructure map is contextual only because the empirical analysis uses annual category-level data rather than port-level observations. The fisheries series comes from the retrospective Agriculture and Fishery Statistics release of the Direção Regional de Estatística da Madeira (DREM, 2025), which covers 1976–2024. Annual Consumer Price Index data used to express monetary values in constant 2024 euros were obtained from the official Instituto Nacional de Estatística CPI service (INE, 2026).

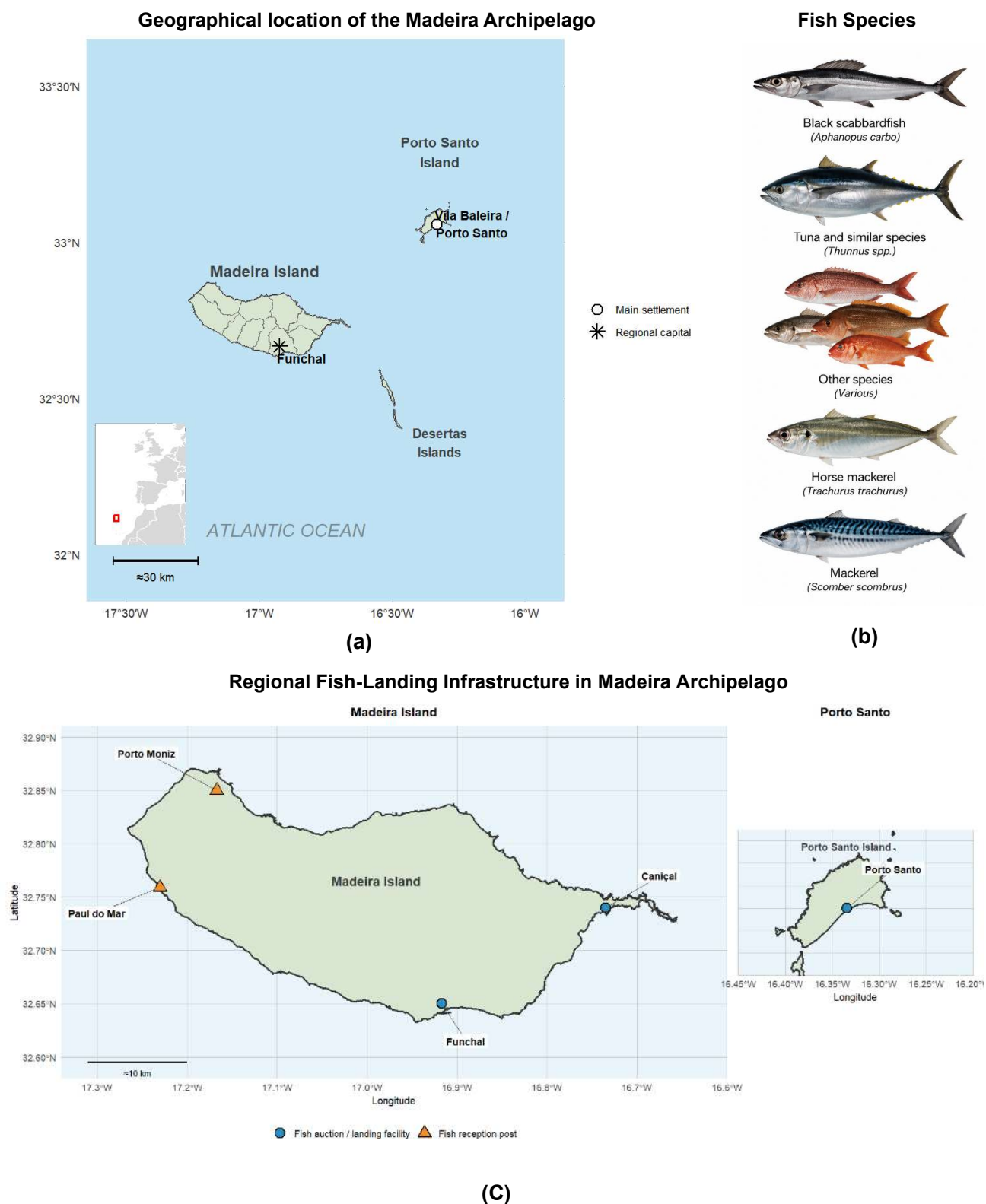


Figure 1. Geographical location, landed categories and fish-landing infrastructure in Madeira. Notes: Panel A shows the Madeira Archipelago; Panel B shows the five landed categories analysed; Panel C shows regional fish auction/landing facilities and fish reception posts. Panel C is provided for context only, as the analysis uses annual landing-category data, not port-level observations. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

The five categories were selected because they are consistently reported throughout 1976–2024 and capture the long-run composition of Madeira's recorded landings. They are treated as statistical landing categories rather than strictly biological species because "tuna and similar species" and "other species" are aggregate groups. This classification is consistent with evidence that Madeira's fisheries are strongly concentrated in black scabbardfish and tuna, with mackerel-type pelagic categories and other fish as recurrent secondary components (Iborra Martín, 2008).

The variables capture physical production, economic value, unit-value dynamics, and landing composition. Landed quantity measures physical output; nominal and real landed values distinguish current-price value from inflation-adjusted value; unit values proxy average landed value per kilogram; and annual shares, HHI, Shannon diversity, and effective-number indicators measure concentration and diversification. These variables are used descriptively and do not represent biological stock status, profitability, or fisher welfare.

For transparency and reproducibility, **Table A1** reports variable definitions, transformations, data sources, and calculation procedures, while **Tables S1–S8** provide validation and supplementary results. The balanced category-year panel contains 245 observations (49 years $\times$ 5 landing categories) and no missing values. Reconciliation differences between official annual totals and the sums of the five category series are negligible: at most 1 tonne in quantity, €2 in nominal value, and €18.18 in real value (**Table S1**).

3.2. Methods

The study applies a descriptive and exploratory strategy to assess long-run structural transformation and value-based economic resilience in Madeira's fisheries sector. Structural transformation is operationally defined as long-run change in landings, real landed value, unit values, landing composition, concentration, and diversity. This definition follows fisheries research that uses species-disaggregated landings and catch composition to evaluate structural change, dependence, diversification, portfolio effects, and resilience (e.g., Albo-Puigserver et al., 2022; Vargas et al., 2022; Monteiro, 2026). Value-based economic resilience is defined narrowly as preservation of part of real landed value despite lower physical landings through unit-value and compositional change; it is not treated as a measure of profitability, welfare, ecological sustainability, or general adaptive capacity.

The empirical design maps directly onto the three hypotheses. H1 is evaluated using first-last changes, compound annual growth rates, subperiod averages, and parametric and non-parametric trend evidence for total landings. H2 is evaluated by comparing the magnitude of change in landed quantity and real landed value, examining endpoint and trend evidence for real unit value, and decomposing the endpoint change in real landed value into quantity, unit-value, and interaction components. H3 is evaluated using quantity- and value-based HHI, Shannon diversity, effective-category indicators, and their long-run trend tests. Trend models qualify the temporal pattern of change rather than override endpoint or subperiod evidence.

The empirical sequence therefore moves from aggregate and category-level description to concentration and diversity, volatility, endpoint real-value decomposition, time-trend evidence, non-parametric robustness checks, and structural-break assessment. Fisheries observations follow the official DREM reporting framework (DREM, 2025), while annual deflation uses the official INE Consumer Price Index service (INE, n.d.). This approach is consistent with the use of official fisheries statistics and monitoring to document sectoral transformation (FAO, 2024; OECD, 2025). Nominal landed values were converted into real 2024 euros using the CPI index, as shown in **Eq. 1**:

$$\text{value_real}_{it} = \text{value}_{it} \times \frac{100}{CPI_t} \quad (\text{Eq. 1})$$

where value_real_{it} is the real landed value of landing category i in year t , value_{it} is the nominal landed value, CPI_t is the Consumer Price Index in the year t , i denotes the landing category, and t denotes the year.

Nominal and real unit values were calculated by dividing landed value by landed quantity expressed in kilograms, as shown in **Eqs. 2–3**, below:

$$\text{unit_value}_{it} = \frac{\text{value}_{it}}{\text{quantity}_{it} \times 1000} \quad (\text{Eq. 2})$$

$$\text{unit_value_real}_{it} = \frac{\text{value_real}_{it}}{\text{quantity}_{it} \times 1000} \quad (\text{Eq. 3})$$

where unit_value_{it} is nominal euros per kilogram, $\text{unit_value_real}_{it}$ is real euros per kilogram at 2024 prices, and quantity_{it} is landed quantity in tonnes. The factor 1000 converts tonnes into kilograms.

Landing-category shares were calculated annually to measure the contribution of each landed category to total listed quantity and value, as shown in **Eqs. 4–5**, below:

$$\text{quantity_share}_{it} = \frac{\text{quantity}_{it}}{\sum_i \text{quantity}_{it}} \quad (\text{Eq. 4})$$

$$\text{value_share}_{it} = \frac{\text{value}_{it}}{\sum_i \text{value}_{it}} \quad (\text{Eq. 5})$$

where $\text{quantity_share}_{it}$ and value_share_{it} are the annual quantity and value shares of landing category i , and each denominator is the annual sum of the corresponding measure across all listed landing categories.

Landing-category concentration was measured using the Herfindahl–Hirschman Index (HHI). In contrast, diversity was measured using the Shannon index and its exponential, interpreted here as the effective number of landing categories. These indicators were calculated separately for quantity and value shares to distinguish physical concentration from economic concentration. This distinction is relevant because landing categories can differ substantially in their quantity and value importance. The measures follow standard concentration and diversity approaches (e.g., Hirschman, 1945; Herfindahl, 1950; Shannon, 1948; Hill, 1973). **Eqs. 6–8** show their construction:

$$\text{HHI}_t = \sum_i s_{it}^2 \quad (\text{Eq. 6})$$

$$\text{Shannon}_t = - \sum_i s_{it} \ln(s_{it}) \quad (\text{Eq. 7})$$

$$\text{Effective_species}_t = \exp(\text{Shannon}_t) \quad (\text{Eq. 8})$$

where s_{it} denotes either $\text{quantity_share}_{it}$ or value_share_{it} , HHI_t is the annual concentration index, Shannon_t is the annual diversity index, and $\text{Effective_species}_t$ is the effective number of landing categories. Higher HHI values indicate greater concentration, whereas lower Shannon and Effective_species values indicate lower diversity, as shown in **Eqs 9–10** below:

$$\text{Change}(\%) = \left(\frac{X_T - X_0}{X_0} \right) \times 100 \quad (\text{Eq. 9})$$

$$\text{CAGR} = \left(\frac{X_T}{X_0} \right)^{1/T} - 1 \quad (\text{Eq. 10})$$

where X_0 is the first observation, X_T is the final observation, and T is the number of annual intervals between the first and final observations. For HHI, Shannon, and effective-category indicators, changes were reported as absolute index-point differences rather than CAGR because these variables are bounded indexes rather than flow variables.

Volatility was measured using the coefficient of variation and the standard deviation of annual log-growth rates, as shown in **Eqs. 11–12**, below:

$$\text{CV}_i = \frac{\text{SD}(X_{it})}{\text{Mean}(X_{it})} \quad (\text{Eq. 11})$$

$$\text{growth}_{it} = \ln(X_{it}) - \ln(X_{it-1}) \quad (\text{Eq. 12})$$

where CV_i is the coefficient of variation for landing category i , $\text{SD}(X_{it})$ is the standard deviation of variable X , $\text{Mean}(X_{it})$ is its mean, and growth_{it} is the annual log-growth rate. These measures were used because the article assesses not only long-run change, but also year-to-year instability by landing category.

Real landed-value change between 1976 and 2024 was decomposed into quantity, unit-value, and interaction effects, as shown in **Eq. 13** below:

$$\Delta V_i = (Q_T - Q_0)P_0 + (P_T - P_0)Q_0 + (Q_T - Q_0)(P_T - P_0) \quad (\text{Eq. 13})$$

where the terms denote the change in real landed value, initial and final landed quantities, and initial and final real unit values for category i . The first term is the quantity effect, the second is the unit-value effect, and the third is the interaction effect. The decomposition distinguishes the arithmetic contributions of physical quantity and unit-value changes to the endpoint difference in real landed value. It is descriptive and is not interpreted as causal evidence. Before estimating the time-series models, we assessed the stationarity of the principal aggregate series using Augmented Dickey–Fuller (Dickey & Fuller, 1979) and KPSS tests (Kwiatkowski et al., 1992). Residual serial correlation in the principal trend regressions was assessed using Breusch–Godfrey tests up to order 3 (Breusch, 1978; Godfrey, 1978) and Durbin–Watson tests (Durbin & Watson, 1950).

Because the principal aggregate trend regressions exhibited serial correlation (**Table S6**), inference for the level-trend models uses Newey–West heteroskedasticity- and autocorrelation-consistent (HAC) standard errors with a lag length of 3 (Newey & West, 1987). The lag specification is consistent with the diagnostic horizon reported in **Table S6**. Given the mixed stationarity evidence, these regressions are interpreted strictly as descriptive trend models: HAC inference addresses residual heteroskedasticity and autocorrelation but does not resolve non-stationarity. The long-run trend models were specified as shown in **Eq. 14** below:

$$y_t = \alpha + \beta Trend_t + \varepsilon_t \quad (\text{Eq. 14})$$

where y_t is the dependent variable in the year t , α is the intercept, $Trend_t$ is the linear time trend, β is the trend coefficient, and ε_t is the error term. These models were used to assess whether aggregate landings, landed values, unit values, concentration, and diversity followed systematic long-run trends.

To complement the parametric models, Mann–Kendall tests and Sen's slope estimators were used to assess monotonic trends without imposing linearity (e.g., Mann, 1945; Sen, 1968; and Kendall, 1975). Bai–Perron tests were used as exploratory checks for discrete structural shifts, with a minimum segment length of eight annual observations and the number of breaks selected by BIC (Bai & Perron, 2003). A failure to select a break is interpreted only as a lack of evidence for a discrete break under this specification, not as proof that no structural change occurred.

4. Empirical results

This section reports the main empirical results on physical contraction, real unit-value adjustment, landing-category specialisation, and value-based economic resilience in Madeira's fisheries sector during 1976–2024.

4.1. Descriptive structure of Madeira's fisheries sector

Table 1 presents descriptive statistics by landing category for the period 1976–2024, including landed quantities, real landed values, unit values, and average quantity and value shares.

Table 1. Descriptive statistics by landing category, 1976–2024

Landing category	N	Mean quantity (t)	SD quantity	Min	Max	Mean real value (€m, 2024)	Nominal unit value (€ / kg)	Real unit value (€ / kg)	Mean quantity share	Mean value share
Black scabbardfish	49	2,468	949	950	4,430	8.68	1.95	4.04	35.8%	44.4%
Tuna and similar species	49	2,960	1,984	260	8,851	7.37	1.6	3.17	38.8%	36.8%
Other species	49	414	190	175	888	2	2.76	4.99	6.5%	10%
Horse mackerel	49	640	460	70	2,006	1.08	1	1.85	9.4%	5.4%
Mackerel	49	659	471	78	1,663	0.69	0.72	1.22	9.6%	3.4%

Notes: N refers to annual observations for 1976–2024. Quantities are in tonnes, real values are in million 2024 euros, and unit values are in euros per kilogram. Shares represent average annual contributions to total quantity and value; percentages may not sum to 100 due to rounding.

The results show a concentrated sectoral structure. Tuna and similar species account for the largest average share of landings (38.8% of quantity), whereas black scabbardfish is the largest value-generating group (44.4% of value). "Other species" has the highest mean real unit value but a limited average share, while horse mackerel and mackerel make smaller

economic contributions. Therefore, Madeira's recorded landings are concentrated in a limited number of economically relevant categories.

4.2. Aggregate long-run changes, 1976–2024

Table 2 reports first-last changes in aggregate landings, landed value, unit value, and concentration/diversity indicators between 1976 and 2024.

Table 2. Aggregate first-last comparison, 1976–2024

Indicator	1976	2024	Change	CAGR
Total landings (t)	6,417	3,517	-45.2%	-1.24%
Nominal landed value (EUR)	645,659	16,724,249	2,490.3%	7.01%
Real landed value (2024 EUR)	17,981,949	16,724,249	-6.99%	-0.151%
Nominal unit value (EUR/kg)	0.101	4.76	4,626.1%	8.36%
Real unit value (2024 EUR/kg)	2.8	4.76	69.7%	1.11%
HHI, quantity shares	0.362	0.495	0.133	NA
HHI, value shares	0.324	0.515	0.191	NA
Shannon diversity, quantity	1.28	0.941	-0.339	NA
Shannon diversity, value	1.27	0.908	-0.364	NA
Effective landing categories, value	3.57	2.48	-1.09	NA

Notes: Monetary values are reported in nominal euros and real 2024 euros. CAGR refers to the compound annual growth rate for 1976–2024. For HHI, Shannon diversity, and effective landing categories, changes are reported as absolute index-point differences; CAGR is not applicable.

The first-last comparison shows substantial net physical contraction. Total landings declined by 45.2%, from 6,417 tonnes in 1976 to 3,517 tonnes in 2024. Nominal landed value increased strongly, but real landed value declined by 6.99%, confirming that nominal growth cannot be interpreted as real economic expansion. Real unit value was 69.7% higher at the endpoints; however, neither the HAC trend model nor the Mann–Kendall test supports a sustained linear or monotonic increase in real unit value. The real-unit-value result is therefore an endpoint comparison rather than evidence of a persistent upward trend. Concentration increased in both quantity and value terms, while Shannon diversity and the effective number of value-relevant categories declined. Taken together, the endpoint evidence indicates physical contraction, partial value-based adjustment, and increasing specialisation.

Figure 2 summarises the aggregate evolution of Madeira's fisheries sector from 1976 to 2024. Panel A shows the uneven trajectory of total landings; Panel B shows nominal landed value; Panel C shows real landed value, which remained far more stable than quantity but exhibits no sustained expansion and is later shown to have a modest negative trend. Panel D shows the divergence between nominal and real unit values.

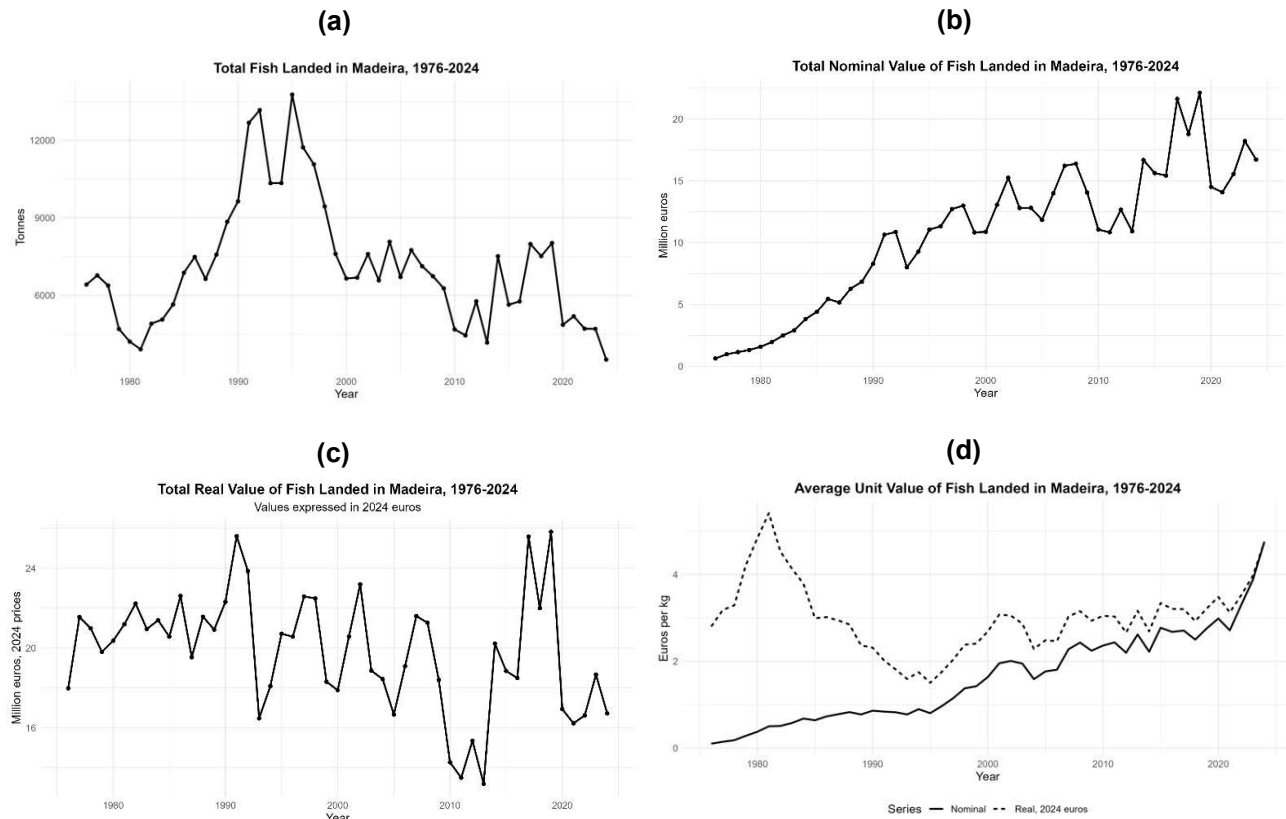


Figure 2. Aggregate evolution of Madeira's fisheries sector, 1976–2024. Notes: Panel A shows total landings; Panel B shows nominal landed value; Panel C shows real landed value at 2024 prices; and Panel D shows nominal and real unit values. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

4.3. Landing-category restructuring

Table 3 reports first-last landing-category changes in landed quantity, real landed value, real unit value, and quantity and value shares between 1976 and 2024.

Table 3. Landing-category first-last comparison, 1976–2024

Landing category	Quantity 1976 (t)	Quantity 2024 (t)	Quantity change	Real value 1976 (€m)	Real value 2024 (€m)	Real value change	Real unit value 1976	Real unit value 2024	Real unit value change	Quantity share Δ (pp)	Value share Δ (pp)
Black scabbardfish	1,062	2,300	117%	6.46	11.39	76.3%	6.08	4.95	-18.6%	48.8	32.2
Mackerel	528	78	-85.2%	0.66	0.19	-70.8%	1.26	2.48	97.5%	-6	-2.5
Horse mackerel	523	70	-86.6%	0.74	0.25	-66.6%	1.42	3.54	149%	-6.2	-2.6
Other species	744	183	-75.4%	2.72	1.36	-50%	3.66	7.45	103%	-6.4	-7
Tuna and similar species	3,561	886	-75.1%	7.39	3.53	-52.3%	2.08	3.98	91.9%	-30.3	-20

Notes: Real values are expressed in million 2024 euros, and real unit values are in euros per kilogram. Quantity and real-value changes are percentage changes between 1976 and 2024; share changes are percentage-point differences.

The endpoint results show strong category-level restructuring. Black scabbardfish was the only category with increases in both landed quantity and real landed value between 1976 and 2024, rising by 117% and 76.3%, respectively, while its real unit value fell by 18.6%. Its quantity and value shares therefore increased substantially. By contrast, tuna and similar species, mackerel, horse mackerel, and other species recorded large endpoint declines in quantity and real landed value; in those declining categories, higher real unit values partly offset the quantity losses.

The category-specific trend models in **Table S3** qualify these endpoint comparisons. Black scabbardfish shows significant positive trends in quantity and quantity share together with a significant negative trend in real unit value. For tuna and similar species, positive trends in quantity and value shares coexist with lower 2024 endpoint shares than in 1976, demonstrating a non-monotonic trajectory and showing why endpoint and trend evidence should not be conflated. Other species, horse mackerel and mackerel, show significant negative trends in quantity, real value, and shares. Overall, the evidence points to increasing structural dependence on black scabbardfish, while tuna remains economically important but comparatively volatile.

Figure 3 shows the category-level evolution of landed quantity and real landed value. Panel A highlights tuna's high variability and the increasing relative importance of black scabbardfish, while Panel B shows how these quantity changes translate into divergent real-value trajectories across the five categories.



Figure 3. Landing-category landed quantity and real value, 1976–2024. Notes: Panel A shows landed quantity in tonnes; Panel B shows real landed value in million 2024 euros. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

Figure 4 shows annual landing-category composition by quantity and value shares. Panel A shows increasing concentration in landed quantity, with black scabbardfish gaining importance and tuna remaining variable. Panel B shows value concentration, dominated by black scabbardfish and tuna. The declining shares of mackerel, horse mackerel, and other species indicate their reduced relative importance over time.

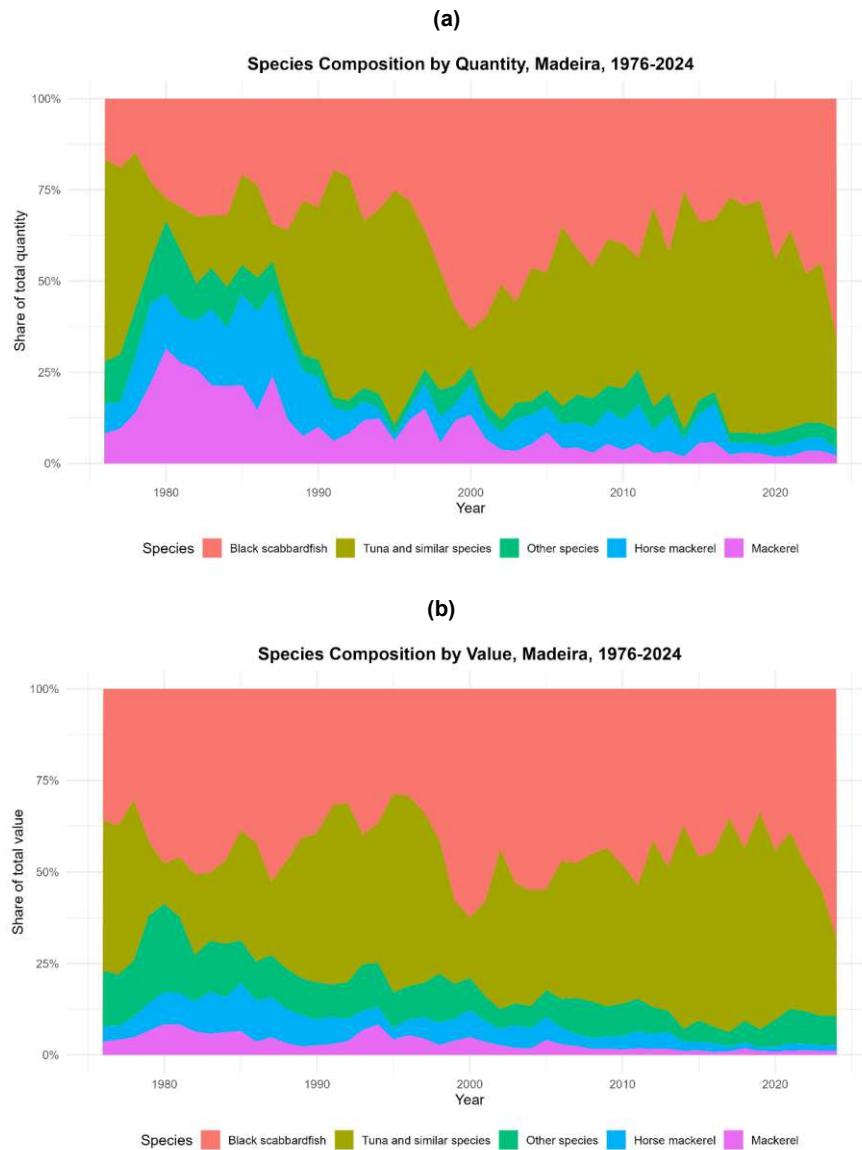


Figure 4. Landing-category composition by quantity and value shares, 1976–2024. Notes: Panel A shows annual quantity shares; Panel B shows annual value shares. Shares are expressed as percentages of annual totals. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

4.4. Period averages, concentration and diversity

Table 4 reports period averages for aggregate landings, real value, real unit value, and value-based concentration and diversity across five subperiods.

Table 4. Period averages for aggregate indicators

Period	Mean landings (t)	Mean real value (€m)	Mean real unit value (€ / kg)	Mean value HHI	Mean Shannon value	Effective value categories
1976-1985	5,488	20.7	3.92	0.309	1.35	3.85
1986-1998	10,209	21.33	2.18	0.338	1.27	3.55
1999-2007	7,198	19.4	2.71	0.397	1.14	3.13
2008-2019	6,211	18.91	3.05	0.414	1.04	2.85
2020-2024	4,597	17.04	3.77	0.43	1.01	2.76

Notes: Values are period averages. Real values are in million 2024 euros, and real unit values are in €/kg. Higher HHI values and lower Shannon/effective-category values indicate greater concentration.

Mean landings peaked in 1986–1998 and declined thereafter, reaching their lowest subperiod average in 2020–2024. Mean real landed value also declined in the most recent period, whereas mean real unit value recovered to €3.77/kg. Over the same subperiods, value HHI increased and both Shannon diversity and the effective number of value-relevant categories declined. These period averages reinforce H1's post-peak contraction pattern and H3's specialisation pattern without implying a smooth year-by-year decline. **Table S4** clarifies the category composition: black scabbardfish had the largest mean value share in 1999–2007 (53.3%) and again in 2020–2024 (50.8%), whereas tuna and similar species had a slightly larger mean value share in 2008–2019 (45.9%, compared with 43.4% for black scabbardfish). Mackerel, horse mackerel, and other species lost relative importance over the long run.

Figure 5 shows the same structural pattern: quantity and value HHI rise over time, whereas Shannon diversity declines for both quantity and value shares. The concentration and diversity indicators therefore provide mutually consistent evidence of increasing landing-category specialisation.

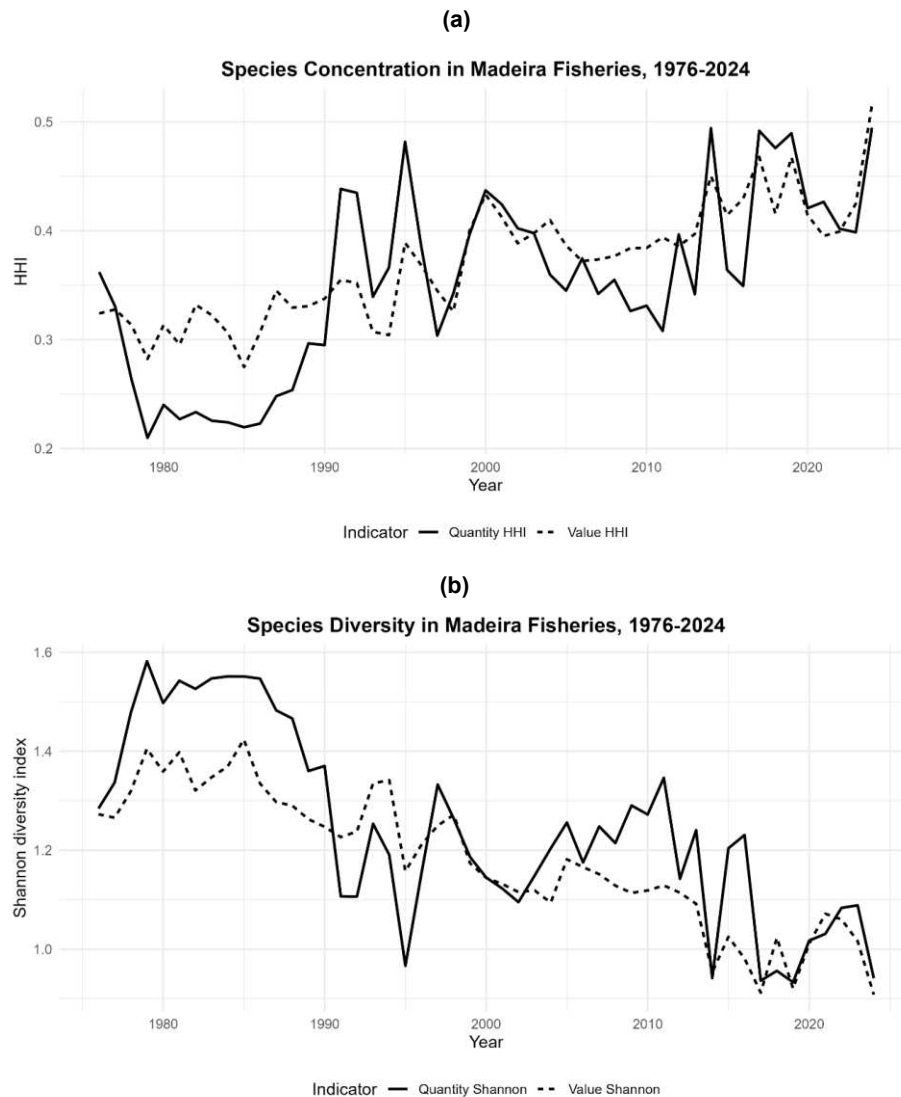


Figure 5. Landing-category concentration and diversity, 1976–2024. Notes: Panel A shows HHI concentration indicators for quantity and value shares; Panel B shows Shannon diversity indicators for quantity and value shares. Higher HHI values indicate greater concentration, while lower Shannon values indicate lower diversity. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

4.5. Growth volatility and real-value decomposition

Table 5 reports landing-category volatility using coefficients of variation (CV) and the standard deviation (SD) of annual log-growth rates for quantity, real value, and unit values.

Table 5. Growth volatility by landing category

Landing category	CV quantity	CV real value	CV nominal unit value	CV real unit value	SD growth quantity	SD growth real value	SD growth real unit value
Tuna and similar species	0.67	0.403	0.598	0.452	0.582	0.405	0.278
Mackerel	0.715	0.648	0.769	0.355	0.425	0.296	0.363
Horse mackerel	0.719	0.615	0.662	0.377	0.386	0.206	0.301
Other species	0.46	0.482	0.66	0.271	0.223	0.207	0.186
Black scabbardfish	0.385	0.185	0.609	0.421	0.141	0.137	0.121

Notes: CV is the coefficient of variation, calculated as the standard deviation divided by the mean. SD growth is the standard deviation of annual log changes.

Volatility differs across categories. Tuna and similar species show the highest annual growth volatility in quantity and real landed value, indicating strong year-to-year instability. Mackerel and horse mackerel also show high quantity variability. Black scabbardfish has the lowest volatility in quantity and real landed value, making it the most stable category on those two dimensions, although not necessarily on every unit-value measure. **Figure 6** summarises these category-level volatility patterns.

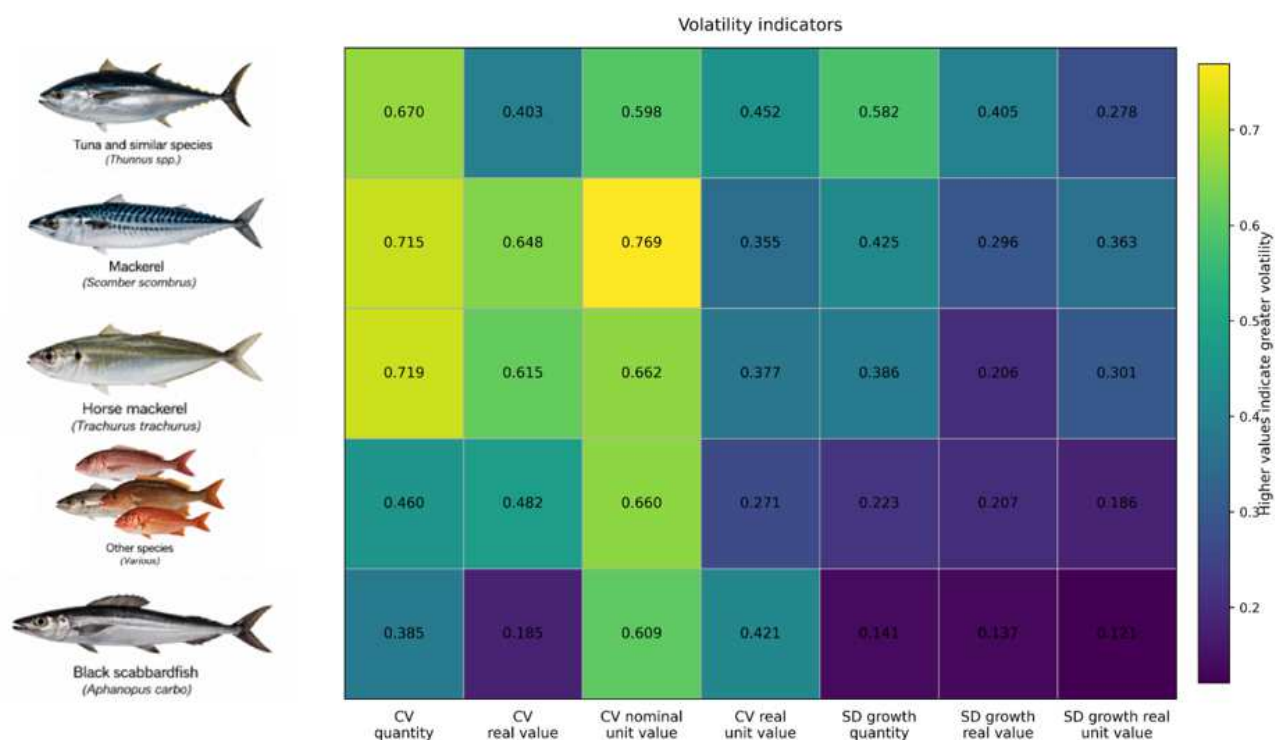


Figure 6. Growth volatility by landing category. Notes: CV denotes the coefficient of variation, and SD growth denotes the standard deviation of annual log changes. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

Table 6 decomposes the change in real landed value between 1976 and 2024 into quantity, unit-value, and interaction effects by landing category.

Table 6. Real value decomposition by landing category, 1976–2024

Landing category	Real value 1976 (€m)	Real value 2024 (€m)	Total change (€m)	Quantity effect (€m)	Unit-value effect (€m)	Interaction effect (€m)
Black scabbardfish	6.46	11.39	4.93	7.53	-1.2	-1.4
Tuna and similar species	7.39	3.53	-3.86	-5.55	6.79	-5.1
Other species	2.72	1.36	-1.36	-2.05	2.82	-2.12
Horse mackerel	0.74	0.25	-0.49	-0.64	1.11	-0.96
Mackerel	0.66	0.19	-0.47	-0.57	0.65	-0.55
Total	18	16.7	-1.26	-1.28	10.2	-10.1

Notes: Values are expressed in million 2024 euros. Unit-value effects partly offset quantity losses, but large interaction terms mean that the decomposition should be interpreted descriptively, not causally.

Total real landed value declined by approximately €1.26 million between 1976 and 2024. Black scabbardfish was the only category with a positive endpoint real-value change, driven primarily by a positive quantity effect. Tuna and similar species, other species, horse mackerel, and mackerel recorded real-value losses. In these declining categories, positive unit-value effects partly offset quantity losses, but negative interaction effects limited that compensation. The decomposition is an accounting identity: it identifies the arithmetic contributions of quantity, unit-value, and interaction terms to the endpoint difference. However, it does not establish causal price or supply responses. **Figure 7** then shows the unconditional relationship between landed quantity and real unit value by category.

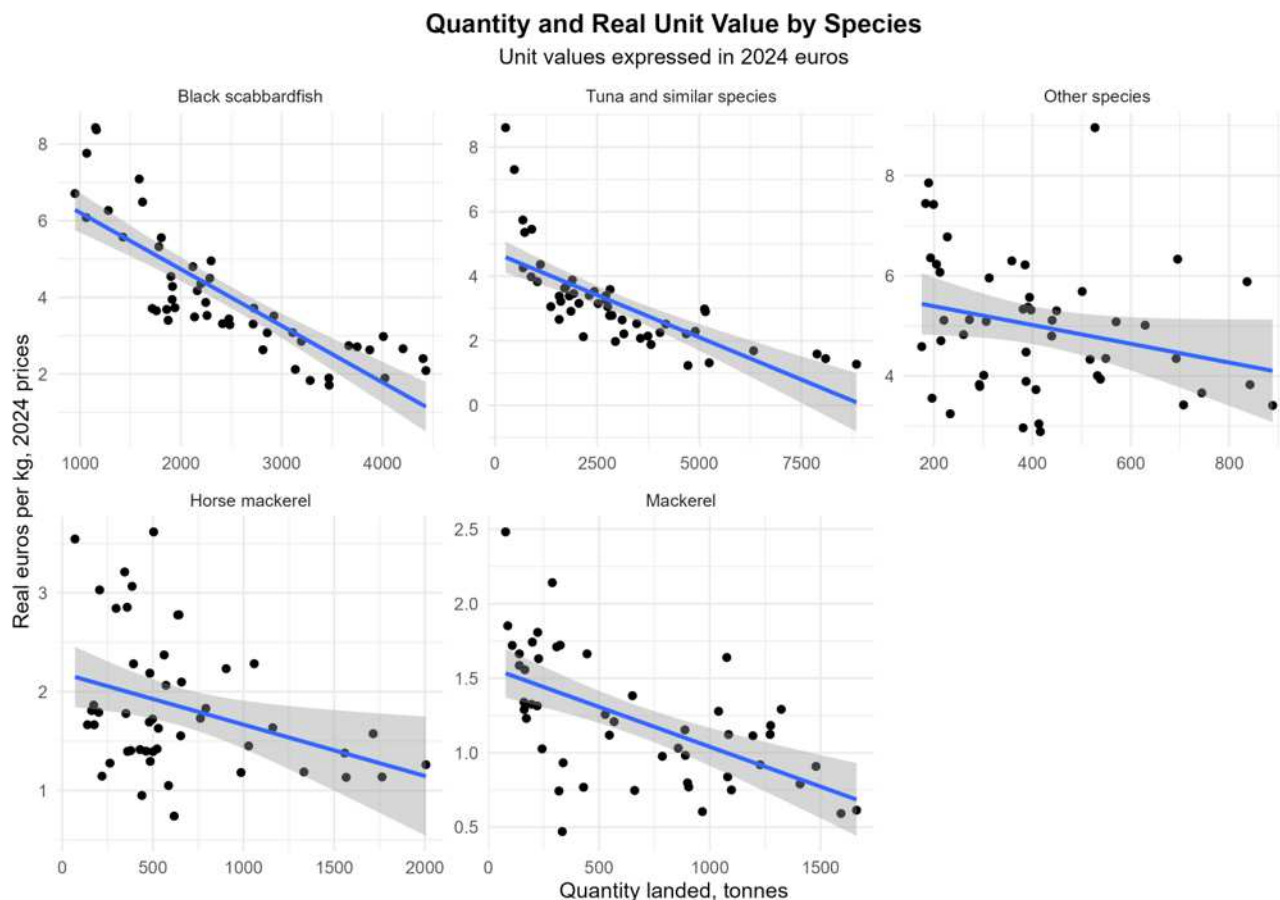


Figure 7. Relationship between landed quantity and real unit value by landing category, 1976–2024. Notes: Points represent annual landing-category observations. Fitted lines show linear associations with 95% confidence intervals. Real unit values are expressed in euros per kilogram at 2024 prices. The authors created this figure using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0.

Figure 7 visually indicates negative fitted associations between landed quantity and real unit value for most categories, although dispersion and apparent strength differ across groups. The pattern is clearest for black scabbardfish, tuna and similar species, and mackerel. Because these are unconditional descriptive associations, they should not be interpreted as

evidence of a causal supply response. Before estimating the descriptive trend models, we examined stationarity and residual diagnostics for the principal aggregate series reported in **Tables S5** and **S6**. **Table S5** shows mixed evidence of stationarity, while **Table S6** identifies serial correlation in the principal regressions. Newey–West HAC standard errors with lag 3 are therefore used for inference, while the level-trend coefficients remain descriptive because HAC adjustment does not resolve non-stationarity.

4.6. Time-series trend evidence

Table 7 reports descriptive long-run trend models with Newey–West HAC standard errors for aggregate quantity, value, unit-value, concentration, and diversity indicators.

Table 7. Long-run trend models with Newey–West HAC standard errors

Model	Term	Estimate	HAC SE	t	p-value
ln_total_quantity	trend	-0.00463	0.00547	-0.85	0.402
ln_total_value_nominal	trend	0.05209	0.00988	5.27	<0.001
ln_total_value_real	trend	-0.00391	0.00182	-2.15	0.037
ln_total_unit_value_nominal	trend	0.05671	0.00675	8.4	<0.001
ln_total_unit_value_real	trend	0.00072	0.005	0.14	0.886
hhi_quantity	trend	0.00401	0.00078	5.13	<0.001
hhi_value	trend	0.00314	0.00029	10.85	<0.001
shannon_quantity	trend	-0.01019	0.00163	-6.26	<0.001
shannon_value	trend	-0.00881	0.00086	-10.3	<0.001
effective_species_value	trend	-0.02857	0.00278	-10.26	<0.001

Notes: All models are descriptive level-trend models. Newey–West HAC standard errors and p-values use lag length 3.

The trend coefficient for total quantity is negative but not statistically significant, so the full sample does not support a robust linear decline in total landings. Nominal landed value and nominal unit value increase significantly, but after CPI adjustment, real landed value shows a modest negative trend and real unit value is not statistically significant. Strong nominal growth therefore did not translate into sustained real expansion. The strongest and most internally consistent trend evidence concerns specialisation: quantity and value HHI increase significantly, while Shannon diversity and the effective number of value-relevant categories decline significantly. These HAC results qualify H1, support the narrow interpretation of H2, and strongly reinforce H3.

Table S7 complements the HAC models with Mann–Kendall and Sen's slope tests. The non-parametric results likewise indicate a significant monotonic decline in real landed value, increasing value concentration, and declining value diversity. In contrast, total quantity and real unit value are not statistically significant. **Table S8** reports that the Bai–Perron procedure selects no structural breaks by BIC. Under the specified minimum-segment and BIC criteria, the data therefore do not support discrete break-point shifts in the principal series; this finding is consistent with, but does not prove, a gradual restructuring process.

4.7. Limitations

This study has several limitations. First, it relies on annual category-level landing statistics. It therefore cannot capture seasonal variation, vessel-level behaviour, fishing effort, fishing-ground heterogeneity, stock abundance, or fisher-level socioeconomic dynamics. Second, some categories are statistical landing groups rather than strictly biological species, and the five-category structure compresses within-group biological heterogeneity. Third, unit values are average landed-value measures rather than direct measures of market price quality, profitability, costs, fisher income, or welfare. Fourth, stationarity and residual diagnostics are reported for the principal aggregate series rather than for every concentration and diversity specification; together with the mixed stationarity evidence, this reinforces the descriptive interpretation of all level-trend estimates. Finally, the correlation, decomposition, concentration, volatility, and trend results do not identify causal ecological or economic drivers. These limitations narrow the scope of inference but do not undermine the dataset's value for documenting long-run structural change and for identifying hypotheses that can be tested with richer effort, biological, market, and vessel-level data.

5. Discussion

The results indicate structural transformation rather than a uniform long-run decline. Endpoint landings fell by 45.2%, from 6,417 tonnes in 1976 to 3,517 tonnes in 2024, while real landed value fell by only 6.99%, from €17.98 million to €16.72 million. Nominal landed value increased by 2,490.3%, but that current-price expansion is not evidence of real

economic growth. Aggregate real unit value rose from €2.80/kg to €4.76/kg between the endpoints, yet neither the HAC nor the Mann–Kendall test identifies a sustained long-run increase. At the same time, real landed value exhibits a modest negative long-run trend. This distinction between endpoint change and trend evidence is central: H1 is supported by net endpoint contraction and declining post-peak subperiod averages, whereas H2 is supported only in a partial, value-based sense because real value contracted far less than physical landings without showing sustained real expansion (DREM, 2025; OECD, 2025; European Commission, 2025).

The concentration indicators provide the clearest evidence of structural specialisation. Value HHI increased from 0.324 to 0.515, Shannon value diversity declined from 1.27 to 0.908, and the effective number of value-relevant categories fell from 3.57 to 2.48. These changes indicate growing dependence on fewer landing categories and a reduced scope for portfolio buffering. The pattern is consistent with earlier descriptions of Madeira as a high-trophic-level, relatively low-diversity fishery strongly dependent on black scabbardfish and tuna (Iborra Martín, 2008; Hermida & Delgado, 2016). It is also consistent with portfolio-effect research showing that diversification can reduce catch and income variability (Vargas et al., 2022). H3 is therefore the hypothesis with the strongest support across endpoint, subperiod, HAC, and non-parametric evidence. Concentration nevertheless remains an indicator of structural dependence and potential exposure, not a direct measure of ecological or socioeconomic vulnerability.

Black scabbardfish was the principal category supporting endpoint real-value preservation. It was the only category with increases in both landed quantity and real landed value between 1976 and 2024, rising by 117% and 76.3%, respectively, even though its real unit value declined by 18.6%. The decomposition attributes its €4.93 million real-value increase mainly to a positive quantity effect of €7.53 million. Aggregate value preservation therefore became more dependent on the performance of one dominant category. This dependence matters for risk assessment because Freitas et al. (2025) document elasmobranch bycatch and management concerns associated with Madeira's fisheries. Evidence from the Portuguese continental black-scabbardfish fishery also illustrates the monitoring demands of deep-water fisheries. However, that evidence is not Madeira-specific and is used here only as contextual comparison (Campos et al., 2025).

Tuna remained economically important but comparatively unstable. Tuna and similar species recorded the highest annual growth volatility in quantity ($SD = 0.582$) and real landed value ($SD = 0.405$). This is compatible with the institutional and market context described by Silva et al. (2025), who identify seasonality, quota constraints, market saturation, landing and transport bottlenecks, catch-quality problems, and labour shortages in the Azores–Madeira pole-and-line supply chain. The present results therefore support treating tuna as an important but volatile component of sectoral value rather than as a uniformly stable source of resilience.

Mackerel and horse mackerel experienced large endpoint quantity declines and high quantity variability, with CV values of 0.715 and 0.719, respectively. Tejerina et al. (2019) document important differences between catches and official landings in Madeira's small-pelagic purse-seine fishery, while Vasconcelos et al. (2024) link long-run small-pelagic dynamics to environmental variability and warming. The weakening of these categories is therefore compatible with climate-sensitive stock dynamics. However, the present design cannot attribute the observed declines to environmental conditions rather than effort, regulation, market conditions, or other drivers.

Taken together, the three hypotheses describe different dimensions of the same restructuring process. H1 is supported by net endpoint and post-peak contraction but not by a significant full-period linear or monotonic trend in total landings. H2 is partially supported because the 45.2% decline in quantity was accompanied by a much smaller 6.99% decline in real landed value and a higher endpoint real unit value. However, neither real landed value nor real unit value shows sustained expansion. H3 is strongly supported because concentration increased and diversity declined across multiple indicators and trend tests. The resulting interpretation is a resilience–specialisation trade-off: partial preservation of real landed value coexisted with increasing dependence on a narrower category base. Broader fishery resilience still depends on ecological, socioeconomic, market, and governance capacities that are not measured by landed value alone (Eurich et al., 2024; Mangubhai et al., 2024). Figure 8 synthesises this analytical chain from the research question and hypotheses to aggregate restructuring, category-level mechanisms, and the resulting resilience–risk trade-off.

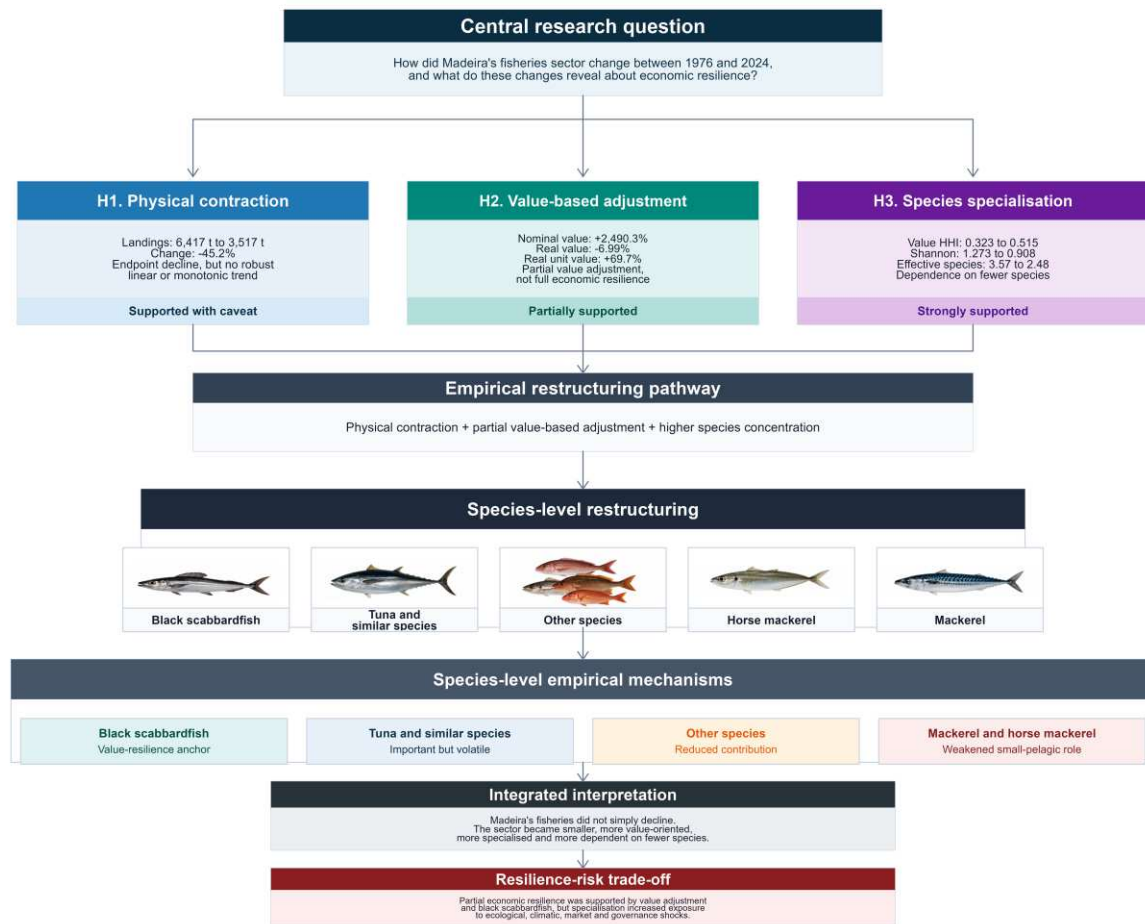


Figure 8. Integrated analytical synthesis of structural transformation and value-based economic resilience in Madeira's fisheries sector, 1976–2024. This figure was created by the authors using R 4.6.1 and ggplot2 4.0.3 in RStudio 2026.07.0. In the schematic, "species" is used as shorthand for the five statistical landing categories analysed in the empirical dataset.

6. Conclusions and policy implications

This study provides an integrated long-run assessment of structural transformation and value-based economic resilience in Madeira's fisheries sector over 1976–2024. The evidence does not support a simple, uniform decline. Endpoint landings fell by 45.2%, and post-peak period averages show substantial contraction, but the full-period HAC and Mann–Kendall tests do not identify a statistically significant linear or monotonic decline in total landings. H1 is therefore supported by endpoint and subperiod evidence, but not by the trend tests, indicating an uneven trajectory rather than a constant rate of contraction.

Value-based adjustment was partial rather than complete. Real landed value declined by 6.99%, much less than the 45.2% contraction in landings, and aggregate real unit value was 69.7% higher at the endpoints. However, real landed value shows a modest negative long-run trend and real unit value shows no significant sustained trend. H2 is therefore only partially supported: unit-value and compositional changes mitigated the value consequences of physical contraction, but they did not generate sustained real-value growth. The decomposition further shows that black scabbardfish was the only category with a positive endpoint change in both quantity and real landed value.

The strongest evidence concerns specialisation. Value HHI increased from 0.324 to 0.515, Shannon value diversity declined from 1.27 to 0.908, and the effective number of value-relevant categories fell from 3.57 to 2.48. In 2020–2024, black scabbardfish and tuna and similar species together represented 88.9% of mean landed value. H3 is therefore strongly supported. This concentration may reduce portfolio buffering and increase potential exposure to disturbances affecting dominant categories, although concentration alone does not establish ecological or socioeconomic vulnerability. The policy implications follow from this narrower interpretation. Long-run monitoring should combine category-resolved landings with fishing effort, CPUE, stock indicators, environmental conditions, vessel characteristics, costs, and fisher-income data so

that changes in resource availability can be distinguished from changes in effort, technology, prices, or markets. Higher unit values should not be treated as proxies for profitability or welfare without corresponding cost and income evidence. Resilience strategies should also assess diversification across catches, products, markets, and value-chain channels, subject to biological sustainability and commercial feasibility. Fleet-modernisation, risk-management, and income-support measures should be evaluated for their effects on effort, profitability, labour retention, fiscal cost, and conservation objectives rather than assumed to strengthen resilience automatically.

Future research should use monthly and vessel-level data where available, distinguish biological species more finely, and link fisheries outcomes to effort, stock status, oceanographic conditions, regulations, labour, and market variables. Causal or quasi-experimental designs would be required to identify the drivers of landings, prices, and income rather than documenting their long-run co-movement. Within the limits of the present descriptive design, the central conclusion is that Madeira's fisheries restructured toward lower physical output and greater concentration while preserving a substantial share of real landed value. The policy challenge is therefore to strengthen resilience without increasing dependence on a narrow biological and economic base.

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Appendix

Table A1. Core variables used in the balanced landing-category-year panel

Field	Status	Calculation/formula	Description	Data source/reference
year	Raw / not transformed	As reported	Calendar year	DREM (2025)
species	Raw/standardised label	Labels translated into English	Statistical landing category	DREM (2025); authors
quantity_t	Raw / not transformed	As reported	Landing-category landed quantity, tonnes	DREM (2025)

Field	Status	Calculation/formula	Description	Data source/reference
value_euros	Raw / not transformed	As reported	Landing-category nominal landed value, euros	DREM (2025)
value_real_2024_euros	Deflated/transformed	$\text{value_euros_it} \times 100 / \text{CPI_t}$	Landing-category real landed value, 2024 euros	DREM (2025); INE (2026); authors
unit_value_eur_per_kg	Calculated	$\text{value_euros_it} / (\text{quantity_t_it} \times 1000)$	Nominal landed value per kilogram	Authors
unit_value_real_2024_eur_per_kg	Calculated from deflated value	$\text{value_real_2024_euros_it} / (\text{quantity_t_it} \times 1000)$	Real landed value per kilogram, 2024 euros	Authors
quantity_share	Calculated	$\text{quantity_t_it} / \sum_i \text{quantity_t_it}$	Landing-category share of annual landed quantity	Authors
value_share	Calculated	$\text{value_euros_it} / \sum_i \text{value_euros_it}$	Landing-category share of annual landed value	Authors
cpi_2024_100	Year-level index	CPI rebased to 2024 = 100	CPI used for deflation	INE (2026); authors
inflation_rate_pct	Year-level raw variable	As reported	Annual CPI inflation rate, percent	INE (2026)
hhi_quantity	Annual calculated index	$\sum_i \text{quantity_share_it}^2$	Quantity-based concentration index	Authors
hhi_value	Annual calculated index	$\sum_i \text{value_share_it}^2$	Value-based concentration index	Authors
shannon_quantity	Annual calculated index	$-\sum_i \text{quantity_share_it} \times \ln(\text{quantity_share_it})$	Quantity-based diversity index	Authors
shannon_value	Annual calculated index	$-\sum_i \text{value_share_it} \times \ln(\text{value_share_it})$	Value-based diversity index	Authors
effective_species_quantity	Annual calculated index	$\exp(\text{shannon_quantity_t})$	Effective number of landing categories by quantity	Authors
effective_species_value	Annual calculated index	$\exp(\text{shannon_value_t})$	Effective number of landing categories by value	Authors

Notes: The panel covers five landing categories observed annually from 1976 to 2024. In the formulas, i denotes landing category, and t denotes year. Quantities are converted from tonnes to kilograms by multiplying by 1000. Monetary variables are expressed in constant 2024 euros using CPI, with 2024 = 100. Value-share indicators are reported once because the annual CPI deflator is common to all landing categories within each year.

Supplementary Files

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- [SupplementarymaterialMK1.docx](#)