Environmental Pollution 396 (2026) 127880

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Stage-dependent trace metal bioaccumulation in *Scomber colias* across the ontogenetic transition

Enrique Lozano-Bilbao [a,b,*], José M. Lorenzo [c], José A. González [c], Alba Jurado-Ruzafa [d], Arturo Hardisson [a], Dailos González-Weller [a,e], Soraya Paz [a], Carmen Rubio [a], Ángel J. Gutiérrez [a]

[a] *Grupo Interuniversitario de Toxicología Ambiental y Seguridad de los Alimentos y Medicamentos, Facultad de Medicina, Universidad de La Laguna (ULL), Campus de Ofra, San Cristóbal de La Laguna, 38071, Santa Cruz de Tenerife, Spain*

[b] *CETIFM (Comportamiento, Ecología Trófica e Impactos en Fauna Marina) Universidad de la Laguna, Departamento Biología animal, Edafologia y Geologia, San Cristobal de La Laguna, Santa Cruz de Tenerife, 38204, Spain*

[c] *Grupo de Investigación en Ecología Marina Aplicada y Pesquerías (EMAP), Instituto de Investigación de Estudios Ambientales y Recursos Naturales (i-UNAT), Universidad de Las Palmas de Gran Canaria, Campus de Tafira, Las Palmas de Gran Canaria, 35017, Las Palmas, Spain*

[d] *Instituto Español de Oceanografía (IEO, CSIC), Centro Oceanográfico de Canarias, Calle Farola del Mar n. 22, 38180, Santa Cruz de Tenerife, Spain*

[e] *Servicio Público Canario de Salud, Laboratorio Central. Santa Cruz de Tenerife, 38006, Santa Cruz de Tenerife, Spain*

ARTICLE INFO

Keywords:
Bioaccumulation patterns
Atlantic chub mackerel
Tipping size
Ontogeny shifts
Benthic
Pelagic

ABSTRACT

Habitat transitions linked to ontogeny can markedly alter contaminant exposure in marine fishes, yet their effects on trace-metal bioaccumulation remain poorly quantified. This study examines how the shift from pelagic to benthic habitats shapes muscle concentrations of aluminium (Al), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb) and zinc (Zn) in the Atlantic chub mackerel *Scomber colias,* a key commercial species in the NE Atlantic. A total of 201 individuals from artisanal fisheries in the Canary Islands were classified as young (<28 cm total length, TL) or mature (≥28 cm TL) adults. Segmented regressions, non-parametric tests, multivariate analyses, functional metal ratios and a Potential Ecological Risk Index were applied. Metal concentrations increased sharply with size, with mature adults showing approximately 6-, 2-, 2.5- and 2-fold higher levels of Cd, Pb, Fe and Zn, respectively, than young adults. Breakpoints in the length–metal relationships occurred between 22.4 and 35.6 cm TL, defining a tipping size near 28 cm that coincides with the onset of benthic feeding. Environmental monitoring and seafood safety risk assessment as well as fisheries management are directly impacted by these findings.

1. Introduction

Metal and trace element contamination of marine ecosystems concerns scientists because it persists, bioaccumulates, and affects aquatic organisms through the trophic web (Cravo and Bebianno, 2005; Saidon et al., 2024). Non-essential metals, and essential metals in high concentrations, unlike many other pollutants, do not undergo biological degradation, and their tissues' build-up in marine organisms may disrupt important physiological functions such as renal function, reproduction, larval development, and redox homeostasis. In this sense, commercially important species play a key role as bioindicators and as a critical source of contaminants to humans (Company et al., 2010; Dallinger and Prosi, 1988).

Many different factors shape the patterns of metal bioaccumulation in teleost fishes such as size, age, sex, diet, habitat, as well as trophic behavior (DeForest et al., 2007; Tsui et al., 2009). During their lifecycle, many marine species undergo ecological shifts linked to different ontogeny and/or biological stages, which implies great changes in the physicochemical environments, in the availability of prey and/or in adaptive physiological mechanisms. Among these drivers, ontogenetic changes in habitat and diet can radically modify the physico-chemical environment experienced by fish, altering both metal bioavailability and uptake routes. As individuals move from pelagic to benthic domains, they encounter different sediment regimes, prey assemblages and redox

* Corresponding author. Grupo Interuniversitario de Toxicología Ambiental y Seguridad de los Alimentos y Medicamentos, Facultad de Medicina, Universidad de La Laguna (ULL), Campus de Ofra, San Cristóbal de La Laguna, 38071, Santa Cruz de Tenerife, Spain.

E-mail address: elozanob@ull.edu.es (E. Lozano-Bilbao).

https://doi.org/10.1016/j.envpol.2026.127880
Received 23 December 2025; Received in revised form 28 January 2026; Accepted 23 February 2026
Available online 24 February 2026

conditions, which together can restructure metal kinetics and storage in tissues. However, the specific contribution of such habitat shifts to trace-metal profiles remains poorly quantified in marine fishes that alternate between pelagic and benthic phases (Karimi et al., 2016; Madigan et al., 2018). These changes potentially influence metal exposure and kinetics. As a result, divergent contamination profiles throughout the lifecycle occur (Endo et al., 2008; Guerriero et al., 2018; Mille et al., 2018; Perugini et al., 2014). In this context, several studies have described ontogeny-related ecological shifts in small and medium pelagic fish, such as migrations to specific habitats for reproductive purposes (Jesus, 1992; Menezes et al., 2006), and depth segregation among size groups (Lorenzo Nespereira, 1992), These ontogenetic shifts are considered a potentially critical determinant of their trace-metal bioaccumulation patterns, yet relatively few studies have explicitly addressed this phenomenon (Báez et al., 2019; Lozano-Bilbao et al., 2020b).

The Atlantic chub mackerel, *Scomber colias*, is an adequate species to study this issue, since it is a pelagic, has ecological and commercial importance, and wide distribution in the Atlantic Ocean and the Mediterranean Sea (Martins et al., 2013; Navarro et al., 2012; Parietti et al., 2025; Sbiba et al., 2024). In *S. colias*, juveniles and young adults inhabit epipelagic waters and feed predominantly on zooplankton, whereas larger adults progressively exploit near-bottom habitats and prey on demersal crustaceans and cephalopods (Chouvelon et al., 2011; Cossa et al., 2012). This ontogenetic habitat shift not only increases contact with metal-rich sediments but also promotes a dietary shift toward higher-trophic-level prey that tend to carry greater metal burdens, making *S. colias* an ideal model to investigate how pelagic–benthic transitions shape metal bioaccumulation.

Notwithstanding the copious literature concerning bioaccumulation in metal in fish, studies assessing how ecological ontogenetic variations in organisms modifies metal profiles throughout species alternating between pelagic and benthic phases remain scarce (Jakimska et al., 2011; Le Croizier et al., 2016a; Mziray and Kimirei, 2016; Ramos-Miras et al., 2019), and any work has addressed this question in a multiscale perspective. This framework melds strong statistical analyses, denotes functional toxicity, and gauges ecological risk. This informational deficit constrains the way we are able to construe fish contamination statistics precisely and compels us to undervalue intraspecific biological diversity (Le Croizier et al., 2016b; Mason et al., 2000; Maz-Courrau et al., 2012; Younis et al., 2015).

Under the hypothesis that the ontogenic transition from a younger adult phase to a mature adult phase of *S. colias* produces marked changes in muscle trace-metal content, the aim of the present study was to quantify how this pelagic–benthic habitat shift affects (i) concentration and co-accumulation patterns of six trace metals, (ii) functional metal ratios related to toxicity and oxidative stress, and (iii) the potential ecological risk associated with each life stage.

2. Material and methods

2.1. Samples collection

A total of 201 Atlantic chub mackerel specimens were obtained during 2021 and 2022 from commercial landings produced by the artisanal fleet operating around Tenerife and Gran Canaria, in the Canary Islands (Fig. 1). Fish were captured using two fishing gears: purse seine, which yielded the smaller individuals (15.73–28.00 cm in length), and handline, which captured the larger specimens (31.10–45.56 cm). These different fishing gears are used in two fishing operations, since

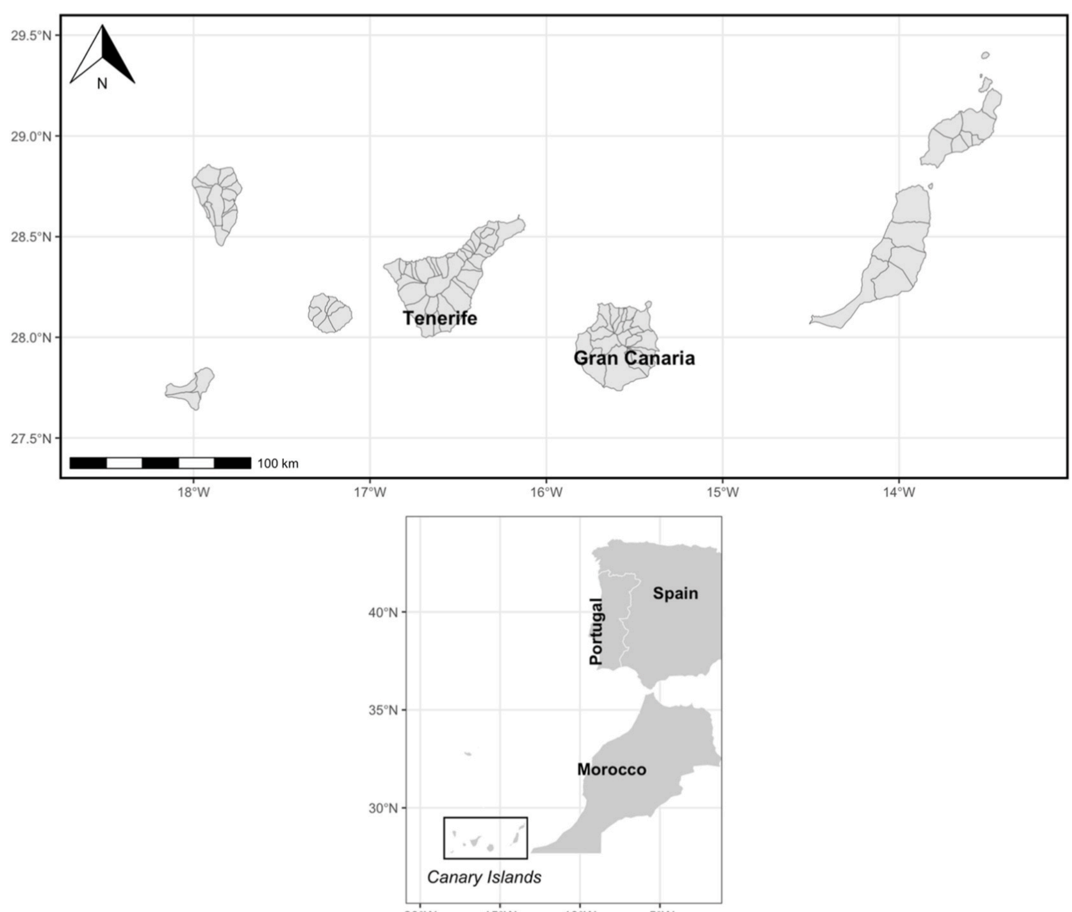

Fig. 1. Geographical location of the islands where the Atlantic chub mackerel individuals used for this study were collected.

purse-seiners generally operates in daily trips close to the coast and handlines are used in longer trips, often targeting greater sizes known to inhabit seamounts in closer areas (Jesus, 1992; Menezes et al., 2006).

After their acquisition, fish were transported to the laboratory on ice to ensure that all specimens remained in comparable optimal condition, wherein total length (TL, cm) was recorded, and dorsal muscle specimens devoid of skin and bone were extracted for subsequent chemical analysis.

2.2. Sample preparation

Firstly, the muscle tissue underwent a 24-h desiccation process inside an oven at 80 °C in order to eliminate samples' moisture. Then, the samples were subjected to a temperature of 450 °C ± 25 °C for 24 to 48 h within a muffle furnace, until they turned into white ashes lacking organic matter. Once the ashing process was complete, the samples were dissolved and filtered in a 1.5% nitric acid (HNO_3) solution, which prevents metal amalgamation, and finally diluted to a final volume of 25 ml. The samples were kept in sterile polypropylene containers and labelled.

The samples' metallic concentration was analysed via inductively coupled plasma optical emission spectrophotometry (ICP-OES), using the Thermo Scientific ICAP 6300 Duo model with an Auto Sampler (CETAX model ASX-520) from Waltham, MA, United States. To evaluate the precision of these determinations, quality control measures were taken and gauged every ten samples. Calibration curves (5 points) were prepared from multi-element standards in the same acid matrix, and each batch included procedural blanks and certified reference materials (DORM-1 and DORM-5) from the National Research Council of Canada, attaining values from 97.1% to 103.2%. Furthermore, instrumental detection and quantification thresholds were determined subsequent to our analysis of 15 designated substances under repeatability circumstances according to the equipment's instrumental reaction (Table 1). Three replicate readings per sample were averaged for each element. The samples were analysed alongside benchmark comparison substances, including blanks. Elements concentrations were obtained for Al, Cd, Cu, Fe, Pb, and Zn, in milligrams by tissue kilogram (wet weight) (Bakircioglu et al., 2013; Khan et al., 2013; Tyler and Yvon, 1995).

2.3. Statistical analysis

The trace metals' contents of Al, Cd, Cu, Fe, Pb, Zn in *S. colias* and their bioaccumulation relationship with the fish size were performed in R environment 4.3.1 (R-Core Team, 2025) and Python 3.11, using a significance threshold of $\alpha = 0.05$. Data were transformed, when appropriate, to meet the assumptions of the statistical tests (de Micheaux et al., 2014; Destefanis et al., 2016; Matloff, 2011; Scavetta and Angelov, 2021).

- *Segmented Regression*

To model possible inflection points in the relationship between total length (TL) with metal concentration, segmented regression models were assayed using the following bilinear model:

Table 1
Limits of detection and quantification of each metal measured by ICP-OES.

Wavelengths of each metal	Detection limit (LD) (μg/L)	Limit of Quantification (LQ) (μg/L)	Recovery (%)
Al (167.0 nm)	4	12	97.1
Cd (226.5 nm)	0.3	1	99.4
Cu (327.3 nm)	4	12	99.1
Fe (259.9 nm)	3	9	98.9
Pb (220.3 nm)	0.3	1	103.3
Zn (206.2 nm)	2	7	100.1

$$Y = \beta_0 + \beta_1 \cdot TL_1 + \beta_2 \cdot TL_2 + \varepsilon$$

W. here Y is the dependent variable under study; β_0, β_1, and β_2 are the regression coefficients; ε is the random error term; TL_1 is the linear term for total length (= minimum TL, break); TL_2 is the quadratic term for total length (= maximum 0, TL – break).

- *Univariate analysis between habitats*

Each metal concentration was compared between young (<28 cm, caught by purse seine) and mature (≥28 cm, caught by handline) adults of *S. colias*. Because the data showed strong skewness and high kurtosis, we used the Mann–Whitney *U* test, a non-parametric procedure that compares whether two independent samples come from the same distribution without assuming normality or homoscedasticity. The direction of the observed effects was consistent, and no p values were close to the chosen significance threshold.

- *Multivariate Analysis*

Principal Component Analysis (PCA) was employed in unsupervised multimetal pattern exploration. To prevent from disparities due to varying initial quantities, every variable was transformed via Z scores.

A Linear Discriminant Analysis (LDA) was used to categorize the specimens according to the metal profiles determined.

- *Correlation in metals' bioaccumulation*

To explore coaccumulation patterns of trace metals in the tissues of *S. colias*, bivariate Pearson correlations were employed using their normalized concentrations. Metal concentrations were normalized using a fourth-root transformation, which reduces the influence of extreme values and helps stabilize variance across samples. This methodology allowed to assess the orientation and magnitude of the linear relationships between pairs of metals. This assessment provides understanding into potential common routes toward uptake, transport, or physiological deposit. In each size grouping, both pelagic and benthic, we computed the Pearson correlation coefficient (r) for every potential metal pairing, analysed distinctly to determine structural variances within the coaccumulation network pertaining to the ontogenetic habitat transition. Values of p below 0.05 constituted the threshold for statistical importance.

- *Functional Metal Ratios*

The metal ratios Cu/Zn and Cd/Pb were explored to analyse possible links with metabolic derangements or stress processes to aggregated exposure. Zinc constitutes a vital enzymatic and structural antioxidant while surplus copper may provoke oxidative stress via the genesis of reactive oxygen species. Cu/Zn ratio functioned as a marker regarding intracellular redox disruption. In contrast, the Cd/Pb ratio signified comparative renal detriment since cadmium manifests superior organ-selective noxiousness inside of excretory tissues and persistently bioaccumulates to a greater extent than lead.

- ***Potential Ecological Risk Index (PERI)***

The Potential Ecological Risk Index (PERI) was calculated following the methodology described by Hakanson (1980), adapted for biological matrices, so that each metal's concentration and toxic potential are combined into a single metric. The specific risk for each element was obtained with the expression:

$$E_{ri} = T_{ri} C_i / C_{background}$$

where E_{ri} is the ecological risk index for metal *i*; T_{ri} is its toxicity coefficient (Cd = 30; Pb = 5; Cu = 5; Fe = 5; Zn = 1; Al = 1); C_i is the muscle concentration in mg/kg; and $C_{background}$ is the background value, defined as the median observed in the young adults group. The total PERI, or global risk index, was obtained by summing all E_{ri}.

The results were interpreted using Hakanson's thresholds: $Eri<40E_{ri}$ indicates low risk; $40 \leq E_{ri} < 80$, moderate risk; $80 \leq E_{ri} < 160$, considerable risk; $160 \leq E_{ri} < 320$, high risk; and $E_{ri} \geq 320$, very high risk. This approach identifies which metals pose the greatest relative threat to organisms and the ecosystem.

3. Results

The summarised descriptive statistics of the muscle trace metals concentrations and morphometrics of the analysed *S. colias* are shown in Table 2.

Segmented regression analysis rised clear discontinuities within the correlation between total length (TL) and metal concentrations showing high concentrations in the accumulation pace throughout fish ontogeny. The models fit to the data quite closely, with the determination coefficients (R^2) between 0.93 and 0.97 (Table 2). Regarding Cd, the main change in slope occurred at 22.4 cm, while Al showed a similar inflection at 22.9 cm, indicating an early onset of increased bioaccumulation. Cu and Pb showed inflection points at 25.8 cm and 26.7 cm, respectively. These tipping points might indicate progressive shifts in habitat utilization. Iron exhibited a unique configuration as the gradient altered remarkably at 30.5 cm (Table 2) (Fig. 2).

Individuals were classified as young adults because the estimated size at first maturity is approximately 19 cm (Jurado-Ruzafa et al., 2021). In addition, the 28 cm threshold was selected because it yields a clear separation of groups in the PCA, and individuals of this size were considered mature given their proximity to the size at Maccoϑ maturation reported in the same study (Jurado-Ruzafa et al., 2021). Young adults (<28 cm) presented a mean TL of 21.54 ± 4.09 cm (range 15.73–28.00 cm) while mature adults (>28 cm) achieved a TL of 36.83 ± 3.24 cm (range 31.10–45.56 cm). The Al proportion augmented by approximately 225% in the group of mature adults. Cd augmented six-fold, increasing from 0.005 mg/kg to 0.029 mg/kg. This is an outstanding discovery considering cadmium's elevated toxicity, although it exists at diminished concentrations. Cu and Fe displayed noticeable increases from 1.08 mg/kg to 2.64 mg/kg, and from 8.75 mg/kg to 21.58 mg/kg, respectively. Pb concentrations increased from 0.067 mg/kg to 0.124 mg/kg. Finally, Zn concentrations were beyond twofold in the mature adults' group, reaching 11.60 mg/kg.

Analysis of metal concentrations in *S. colias* revealed noticeable differences linked to fish size. The studied metal concentrations substantially augmented in the mature adults (≥28 cm). For the U-Mann Whitney test, the p-value resulted $<10^{-31}$ for each assessment (Table 2). Segmented-regression analysis pinpointed definitive alterations within metal accretion with respect to TL (Table 2).

At the multivariate level, principal component analysis (PCA), an ordination technique that summarizes variation in a set of correlated variables into a few synthetic axes, highlighted the separation between young and mature adults in factorial space, with the first two axes explaining more than 70% of the total variance (Fig. 3). The metals Al, Fe and Zn contributed most strongly to the primary gradient, indicating that these elements are key drivers of the multi-metallic profile, which achieved an overall classification accuracy above 95% (Fig. 3). The model displayed high sensitivity for the group of bigger fish and high specificity for the smaller fish group, underscoring the reliability of metal bioaccumulation as an ecological marker.

Correlation analysis of metal concentrations unveiled connections that diverged substantially among fish groups. Regarding the general scope, given that r exceeded 0.80, important positive correlations were observed among Al, Fe and Zn, implying either co-accumulation or else a shared environmental source is influencing them. Ordinarily, correlations weaker and more dispersed with r values rarely exceeding 0.60, existed among young adults. Conversely, the mature adults' group presented a uniform configuration. A powerful Zn–Cu correlation (r = 0.89 - mature adults) underscored this trend alongside a very strong Fe–Al bond (r = 0.92 - young adults) (Fig. 4).

The functional metal ratios displayed trends that were physiologically relevant. On account of its indication of redox equilibrium, the Cu/Zn ratio was elevated within mature adult fish (0.244 vs 0.199), implying a transition toward more oxidative-stress conditions. The Cd/Pb proportion, showed a mean value of 0.235 in mature adults as opposed to a value of 0.065 in the younger ones. Results appeared throughout a wider assessment in proportions like Zn/Fe as well as Cu/Fe, although with diminished explicit physiological validation (Table 3).

The potential ecological risk index (PERI) showed that mature adult fish accumulate Cd and Pb at levels that place them in the "considerable" and "high" risk categories, respectively. The overall risk index (E_{ri} for mature adults was 223, which corresponds to a high ecological threat under Hakanson's classification. In contrast, young adults scored markedly lower ($E_{ri} = 84$), reinforcing the existence of gradual pattern in contaminant exposure. The multi-metal fingerprint, represented as a heat-map ordered by TL (Fig. 5), distinctly showed the way that each metal concentration progressively augmented as fish grew. Cd, Al, and Pb followed this tendency quite markedly, as their signal intensities increased in the direction of the larger sizes. The average spider diagram for benthic organisms displayed a broader and more vertically elongated profile. Particularly prominent disparities existed within Fe, Cd, also Zn. Subsequently, the co-accumulation network connected greatly more in the benthic group since nodes were densely linked, especially among Fe, Al, Zn and Pb. While the pelagic network fragmented further and feebler correlations.

4. Discussion and conclusions

Our results therefore support the view that the pelagic–benthic transition constitutes a critical bottleneck for metal accumulation in *S. colias*, where simultaneous changes in habitat, prey and physiology converge to amplify tissue metal loads. This study confirms that trace-metal bioaccumulation profiles experience a deep transformation in *S. colias* around a size of roughly 28 cm TL. The transition is clear not

Table 2
Descriptive statistics (mean ± standard deviation (min–max) of the metal content (mg/kg of wet weight) in *S. colias*. Other statistical analyses used a p-value <0.05* (U-Mann Whitney, Segmented regression).

	Capture		U-Mann Whitney test	Segmented regression	
	Purse seine	Handline		Breaking Point (cm)	R^2
Total length (cm)	21.54 ± 4.09 (15.73–28.00)	36.83 ± 3.24 (31.10–45.56)	-	-	-
Al	5.75 ± 1.93 (3.32–10.52)	18.86 ± 2.64 (11.70–24.23)	5.01e-32*	22.9	0.95
Cd	0.005 ± 0.004 (0.001–0.014)	0.029 ± 0.007 (0.015–0.043)	5.01e-32*	22.4	0.97
Cu	1.08 ± 0.23 (0.86–1.73)	2.64 ± 0.53 (1.94–4.47)	5.00e-32*	25.8	0.96
Fe	8.75 ± 1.10 (6.40–11.39)	21.58 ± 5.87 (11.97–39.57)	5.01e-32*	30.5	0.95
Pb	0.067 ± 0.009 (0.035–0.087)	0.124 ± 0.017 (0.092–0.174)	5.01e-32*	26.7	0.94
Zn	5.45 ± 0.59 (1.90–6.51)	11.60 ± 4.61 (6.23–22.72)	5.48e-32*	35.6	0.93

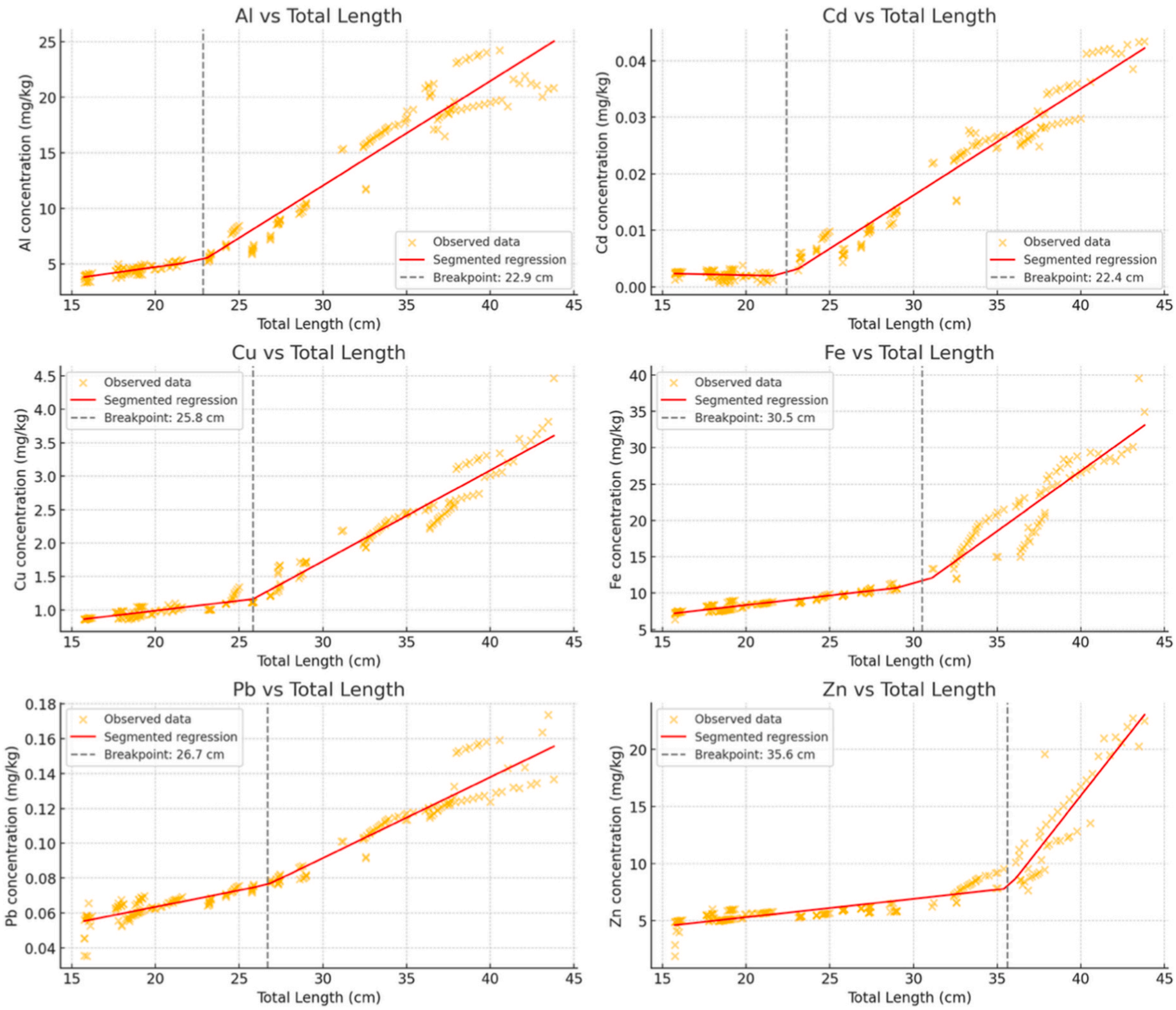

Fig. 2. Segmented regression graphs for each metal concentration found in *S. colias* in relation to total length. The grey segmented lines indicate the breakpoints. Breakpoint and R^2 values for each model are reported in Table 2.

only in each element's absolute concentrations but also in the way the metals interact, and how they bioaccumulates in the muscle, probably reflecting ecological pressures, physiological adaptations, and local environmental conditions (Bánfalvi, 2011; Castro-González and Méndez-Armenta, 2008; Saidon et al., 2024; Stillman, 1995; Tvermoes et al., 2015). Principal component analysis (PCA) clearly discerns young and mature adults. PCA elucidates >70% of the variance upon the first two axes, indicating the shift is abrupt rather than gradual. Younger adult Atlantic chub mackerel (<28 cm) primarily feed on zooplankton and therefore exhibit low cumulative metal contents, with relatively low concentrations of Cd (0.005 mg/kg), Fe (8.75 mg/kg) and Zn (5.45 mg/kg). In contrast, Cd, Fe and Zn concentrations increase markedly in mature adults, a pattern that is consistent with, although does not by itself prove, a dietary shift toward larger demersal prey occupying higher trophic levels and typically exhibiting higher metal loads. Existing diet studies for *S. colias* and related species support this interpretation, but direct dietary and isotopic data would be required to confirm the relative contribution of trophic vs. environmental pathways in this system.

(Bouzzammit et al., 2022a; Ferreira et al., 2020; Gushchin and Corten, 2017). This alteration is supported by in morphofunctional substantiation.

Throughout its lifecycle, *S. colias* exhibits the following pattern: juveniles and young adults inhabit shallower, open-water habitats (pelagic phase), whilst larger adults generally migrate toward benthic zones, where they prey on demersal organisms (Lorenzo Nespereira, 1992). This habitat shift may considerably alter contaminant exposure, altering the intrinsic physiological processes concerning trace elements and metal absorption, allocation, and elimination (Fátima et al., 2015; Keč and Zorica, 2013; Velasco et al., 2011; Villamor et al., 2017a). The observed variance in metal composition and inter-metal correlations suggests that the seabed substrate not only increases metal bioavailability but also concentrates trace substances, thereby enhancing bioaccumulation in bottom-dependent organisms.

Benthic organisms exhibit a robust, systematic co-accumulation pattern that appears to be linked to diet, thereby driving increased and synchronized metal uptake (Clements et al., 2000; Frontalini and Coccioni, 2008; Luoma and Carter, 2020; Ryu et al., 2011). Segmented regression analyses corroborate that this alteration manifests at tipping sizes: Cd and Al disrupt prematurely at about 22 cm TL, whereas Fe changes direction at 30.5 cm TL. Bioaccumulation shows changes in the accumulation slope ($R^2 > 0.94$), suggesting distinct eco-physiological stages; therefore, it does not increase linearly with body size. Certain elements seem to denote this shift at smaller sizes, while others incorporate more deeply into the benthic ecosystem (Chakraborty et al., 2014; Cibic et al., 2012; Hwang et al., 2019; Kumar et al., 2020; Lens et al., 2005). This ontogenetic shift is mirrored physiologically by an increase in the Cu/Zn ratio from 0.199 to 0.244, a recognised indicator of oxidative stress that reflects a relative rise in pro-oxidant Cu over antioxidant Zn. Likewise, the Cd/Pb ratio rises from 0.065 to 0.235, suggesting a disproportionate accumulation of Cd, which has been associated with enhanced tissue retention and potential renal

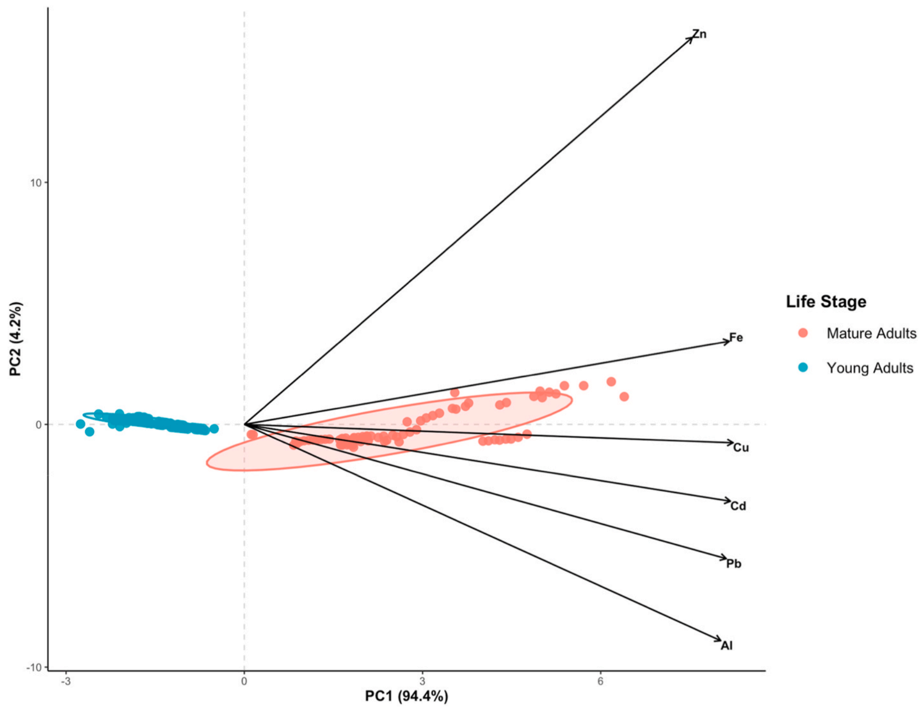

Fig. 3. Principal Component Analysis (PCA) biplot of trace metal concentrations in *Scomber colias*. The figure displays the ordination of individual specimens (young adults <28 cm in cyan, mature adults ≥28 cm in red) according to the first two principal components. Vectors represent the contribution and direction of each metal variable in the multivariate space. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

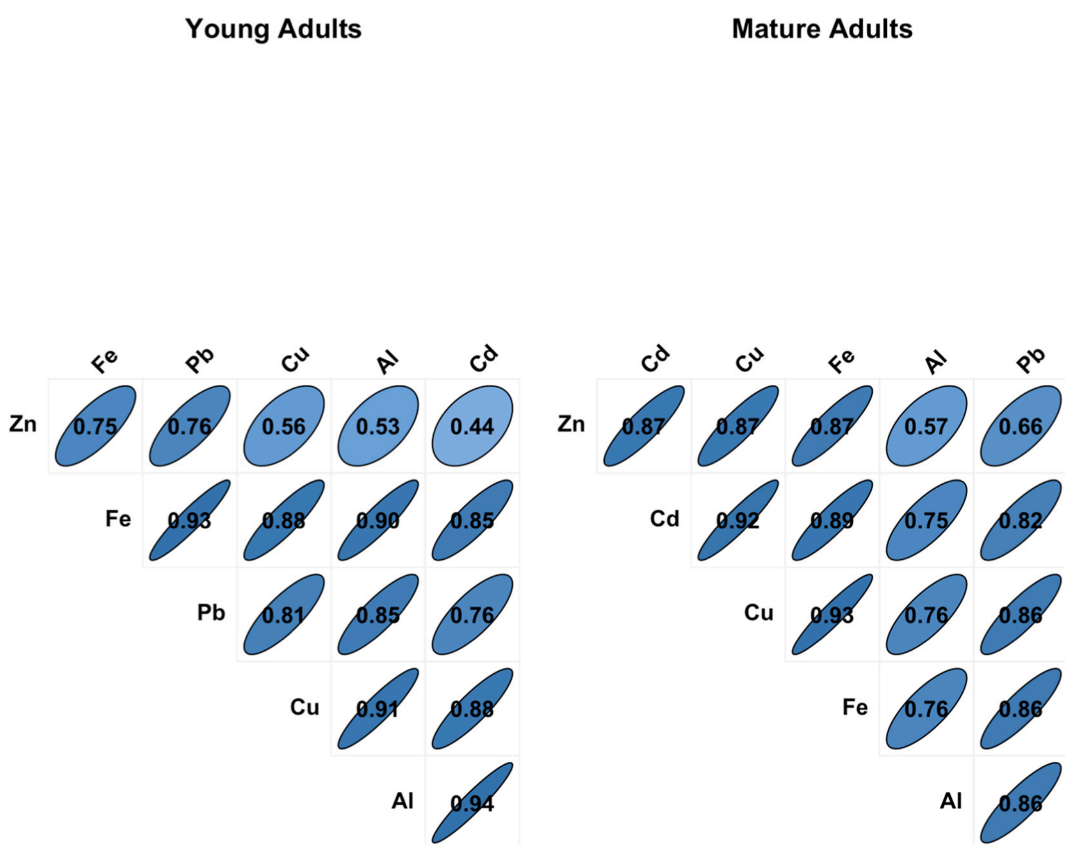

Fig. 4. Pearson correlation matrices ($p < 0.05$) for trace metal concentrations in young and mature *Scomber colias*. The figure shows pairwise correlation coefficients among metals. Ellipses illustrate the strength and direction of correlations, with the size and elongation of the ellipses indicating the magnitude of the relationship.

Table 3
Mean ± sd (standard deviation) values for the metal ratios Cu/Zn and Cd/Pb found in S. colias.

	Cu/Zn	Cd/Pb
Mature adults	0.244 ± 0.047	0.235 ± 0.031
Young adults	0.199 ± 0.040	0.065 ± 0.042

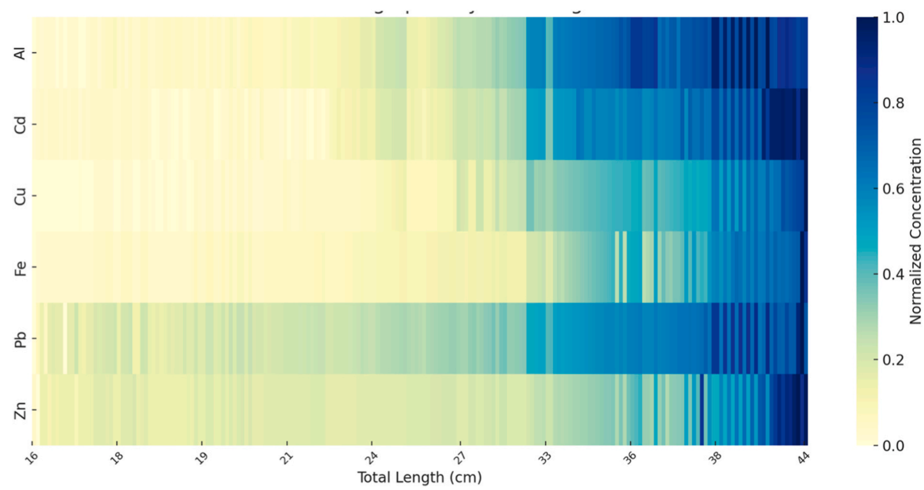

Fig. 5. Multi-metal fingerprint graph with the normalized mean for each metal and sizes (TL). Each column corresponds to an individual specimen arranged by increasing TL, and each row represents one metal. The color scale indicates normalized concentration values, with darker shades representing higher normalized levels. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

impairment (Javed and Usmani, 2013; Rahman et al., 2019; Silva and Martinez, 2007). This shift is consistent with maturity-related changes that can increase the integration of exposure pathways and reinforce physiological regulation of uptake, internal distribution, and retention (Rainbow, 2007). Overall, the data support stage-dependent bioaccumulation dynamics rather than a simple, size-proportional increase (Charles et al., 2020; Heithaus and Vaudo, 2004; Lozano-Bilbao et al., 2023; Scott et al., 2012).

These ontogeny changes also impacted the ecological risk index (PERI): elevated Cd along with Pb concentrations chiefly cause mature adults of *S. colias* to reach the high-risk category (Eri = 223), while young adults remain at moderate levels (Eri = 84). This disparity shows that environmental conditions can shape the adult stages. As individuals mature and their reproductive capacity increases, benthic habitats may become more important as spawning areas because they can offer better access to key micronutrients such as Fe and P, more stable temperatures, and physical structure that can support courtship and mating behaviour, while surface turbulence is less influential along the migratory route (Ciannelli et al., 2015; Lall and Kaushik, 2021; Taylor et al., 2019). A shift in habitat use may also reduce parasite pressure, particularly from pelagic ectoparasites, which could lower energetic costs before reproduction (Afonso et al., 2008; Caddy, 2008; Kime, 1995). Behavioural processes may also promote movement toward near bottom habitats. Juveniles may follow older individuals to feeding grounds, and feeding related sounds and substrate vibrations can act as aggregation cues. These mechanisms can facilitate the ontogenetic transition by improving foraging efficiency. (Brazenor et al., 2020; Pryor and Casto, 2017).

S. colias is a high commercially valued species (Baye Braham et al., 2021), thus the accumulation of toxic metals within it is concerning (Artemenkov et al., 2021; Villamor et al., 2017b). This accrual throughout the mature adult phase may pose a hazard to human consumers and higher-level predators, particularly where muscle concentrations approach or exceed regulatory limits for fish muscle (0.30 mg/kg wet weight for Pb and 0.05 mg/kg for Cd in the EU (EFSA, 2011; 2010)). Such concern is supported by existing regulatory thresholds that explicitly link maximum permissible metal levels to fish size or life stage, thereby constraining consumption for larger, older individuals. In this framework, relating the observed body burdens to health-based guidance values, such as the tolerable weekly intake for Cd of 2.5 μg/kg body weight, provides a direct measure of dietary risk for frequent consumers. Therefore, *S. colias* may serve as a useful bioindicator of benthic metal contamination, given the stable multi-metal profile documented in benthic-feeding specimens, particularly in benthic systems subjected to anthropogenic impact (Bouzzammit et al., 2022b; Duarte et al., 2025; Lozano-Bilbao et al., 2024b, 2024a; Rivas-Mena et al., 2024; Valente et al., 2025).

From a broader ecological perspective, the ontogenetic pattern observed in *S. colias* is consistent with niche-shift theory, whereby changes in space use and trophic level during growth reconfigure both resource acquisition and contaminant exposure (Sánchez-Hernández et al., 2019). In this species, the transition from a pelagic, zooplanktivorous phase to a benthic, higher-trophic-level phase resembles patterns described for other marine fishes in which life-history transitions amplify biomagnification of metals and other pollutants. Such stage-structured exposure has important implications for food-web models and for the design of monitoring programmes targeting life stages that act as contaminant “bottlenecks” in marine ecosystems (Kraemer et al., 2012; Oros, 2025).

In order to illuminate intrinsic detoxification processes, subsequent studies should integrate stable-isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) to quantify more accurately trophic variations, and using molecular methodologies (e.g., transcriptomics of metallothioneins and antioxidant enzymes). Since clear seasonal, interannual and geographical patterns have been observed for the Atlantic chub mackerel, these fluctuations should also be considered in further analyses, furthermore, environmental-monitoring protocols coupled with fisheries management protocols (Domínguez-Petit et al., 2025; ICES, 2021). This study has some limitations. First, we inferred dietary and habitat shifts from published information and size structure rather than from direct data (e.g. stomach contents, stable isotopes or telemetry). Second, sampling was restricted to two years and two islands, which may not capture the full spatial and interannual variability in metal exposure. Finally, we focused on muscle tissue only; including liver, gill and kidney would provide a more complete picture of metal dynamics and detoxification. Future work combining biochemical, isotopic and tagging approaches across seasons and regions would help to refine these inferences.

CRediT authorship contribution statement

Enrique Lozano-Bilbao: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José M. Lorenzo:** Writing – original draft, Validation, Methodology, Investigation. **José A. González:** Writing – original draft, Supervision, Investigation. **Alba Jurado-Ruzafa:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Arturo Hardisson:** Writing – original draft, Supervision, Software, Resources, Project administration, Funding acquisition. **Dailos González-Weller:** Writing – original draft, Software, Project administration, Methodology. **Soraya Paz:** Writing – review & editing, Resources, Investigation, Data curation. **Carmen Rubio:** Writing – original draft, Supervision, Data curation. **Ángel J. Gutiérrez:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Consent to participate

For the study, no animals had to be killed, so it is not applicable.

Ethics approval

All authors declare that the use of animals for this research complies with the requirements of the European legislation on the use of animals for experimentation with the Code of Practice for Housing and Care of Animals Used in Scientific Procedures.

Consent for publication

The authors consent the publication of this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.127880.

Data availability

Data will be made available on request.

References

Afonso, P., Morato, T., Santos, R.S., 2008. Spatial patterns in reproductive traits of the temperate parrotfish Sparisoma cretense. Fish. Res. 90, 92–99.
Artemenkov, D.V., Mikhailov, A.I., Nikitenko, A.I., Sobolev, I.V., Belyaev, V.A., 2021. Population dynamics of Atlantic chub Mackerel Scomber colias at the multispecies fishery. J. Ichthyol. 61, 900–911.
Báez, J.C., Rodriguez-Cabello, C., Banon, R., Brito, A., Falcon, J.M., Mano, T., Baro, J., Macias, D., Meléndez, M.J., Camiñas, J.A., 2019. Updating the national checklist of marine fishes in Spanish waters: an approach to priority hotspots and lessons for conservation. Mediterr. Mar. Sci. 20, 260–270.
Bakircioglu, D., Kurtulus, Y.B., Yurtsever, S., 2013. Comparison of extraction induced by emulsion breaking, ultrasonic extraction and wet digestion procedures for determination of metals in edible oil samples in Turkey using ICP-OES. Food Chem. 138, 770–775. https://doi.org/10.1016/j.foodchem.2012.10.089.
Bánfalvi, G., 2011. Heavy metals, trace elements and their cellular effects. Cellular effects of heavy metals 3–28.
Baye Braham, C., Bensbai, J., Canha, A.M.L., Carrera, P., Chaves, C., Derhy, G., Fernandes, A.C., Feijó, D., Garrido, S., Jeyid, M.A., 2021. Second Workshop on Atlantic Chub Mackerel (Scomber Colias). Centro Oceanográfico de Canarias.
Bouzzammit, N., El Habouz, H., Okba, Z., El Ouizgani, H., 2022a. Diet composition and feeding strategy of Atlantic chub mackerel Scomber colias in the Atlantic coast of Morocco. Annales: Series Historia Naturalis. Scientific and Research Center of the Republic of Slovenia 377–390.
Bouzzammit, N., El Habouz, H., Okba, Z., El Ouizgani, H., 2022b. Diet composition and feeding strategy of atlantic CHUB mackerel SCOMBER colias in the atlantic coast of Morocco. In: Annales: Series Historia Naturalis. Scientific and Research Center of the Republic of Slovenia, pp. 377–390.
Brazenor, A.K., Francis, D.S., Conlan, J.A., Carton, A.G., Hutson, K.S., 2020. Temperature alters reproduction and maternal provisioning in a fish ectoparasite. Int. J. Parasitol. 50, 839–849.
Caddy, J.F., 2008. The importance of “cover” in the life histories of demersal and benthic marine resources: a neglected issue in fisheries assessment and management. Bull. Mar. Sci. 83, 7–52.
Castro-González, M.I., Méndez-Armenta, M., 2008. Heavy metals: implications associated to fish consumption. Environ. Toxicol. Pharmacol. 26, 263–271. https://doi.org/10.1016/j.etap.2008.06.001.
Chakraborty, S., Bhattacharya, T., Singh, G., Maity, J.P., 2014. Benthic macroalgae as biological indicators of heavy metal pollution in the marine environments: a biomonitoring approach for pollution assessment. Ecotoxicol. Environ. Saf. 100, 61–68.
Charles, W.D., Hazin, H., Travassos, P., 2020. Interactions between cetaceans and the tuna/swordfish pelagic longline fishery in the tropical western Atlantic Ocean. Fish. Res. 226, 105530.
Chouvelon, T., Spitz, J., Cherel, Y., Caurant, F., Sirmel, R., Mèndez-Fernandez, P., Bustamante, P., 2011. Inter-specific and ontogenic differences in δ13C and δ15N values and Hg and Cd concentrations in cephalopods. Mar. Ecol. Prog. Ser. 433, 107–120.
Ciannelli, L., Bailey, K., Olsen, E.M., 2015. Evolutionary and ecological constraints of fish spawning habitats. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 72, 285–296.
Cibic, T., Franzo, A., Celussi, M., Fabbro, C., Del Negro, P., 2012. Benthic ecosystem functioning in hydrocarbon and heavy-metal contaminated sediments of an Adriatic lagoon. Mar. Ecol. Prog. Ser. 458, 69–87.
Clements, W.H., Carlisle, D.M., Lazorchak, J.M., Johnson, P.C., 2000. Heavy metals structure benthic communities in Colorado mountain streams. Ecol. Appl. 10, 626–638.
Company, R., Felícia, H., Serafim, A., Almeida, A.J., Biscoito, M., Bebianno, M.J., 2010. Metal concentrations and metallothionein-like protein levels in deep-sea fishes captured near hydrothermal vents in the Mid-Atlantic Ridge off Azores. Deep. Sea. Res. 1 Oceanogr. Res. Pap. 57, 893–908. https://doi.org/10.1016/j.dsr.2010.02.005.
Cossa, D., Harmelin-Vivien, M., Mellon-Duval, C., Loizeau, V., Averty, B., Crochet, S., Chou, L., Cadiou, J.-F., 2012. Influences of bioavailability, trophic position, and growth on methylmercury in hakes (Merluccius merluccius) from Northwestern Mediterranean and Northeastern Atlantic. Environ. Sci. Technol. 46, 4885–4893.
Cravo, A., Bebianno, M.J., 2005. Bioaccumulation of metals in the soft tissue of Patella aspera: application of metal/shell weight indices. Estuar. Coast Shelf Sci. 65, 571–586. https://doi.org/10.1016/j.ecss.2005.06.026.
Dallinger, R., Prosi, F., 1988. Heavy metals in the terrestrial isopod Porcellio scaber Latreille. II. Subcellular fractionation of metal-accumulating lysosomes from hepatopancreas. Cell Biol. Toxicol. 4, 97–109. https://doi.org/10.1007/BF00141289.
de Micheaux, P.L., Drouilhet, R., Liquet, B., 2014. The R Software: Fundamentals of Programming and Statistical Analysis. Springer Science & Business.
DeForest, D.K., Brix, K.V., Adams, W.J., 2007. Assessing metal bioaccumulation in aquatic environments: the inverse relationship between bioaccumulation factors, trophic transfer factors and exposure concentration. Aquat. Toxicol. 84, 236–246. https://doi.org/10.1016/j.aquatox.2007.02.022.
Destefanis, G., Ortu, M., Porru, S., Swift, S., Marchesi, M., 2016. A statistical comparison of java and python software metric properties. In: Proceedings of the 7th International Workshop on Emerging Trends in Software Metrics, pp. 22–28.
Domínguez-Petit, R., Cousido-Rocha, M., Pennino, M.G., Abad, E., Riveiro, I., Costas, G., Cerviño, S., 2025. Environmental drivers of mean weight-at-age variability in pelagic and benthic fish from the NW Iberian Peninsula. Hydrobiologia 852 (4), 805–821.
Duarte, B., Feijão, E., Cruz-Silva, A., Pascoal, P., Nunes, M., Pereira, M., Figueiredo, A., Dias, R.P., Tanner, S.E., Fonseca, V.F., 2025. Reveal your microbes, and i'll reveal your origins: geographical traceability via Scomber colias intestinal tract metagenomics. Anim. Microbiome 7, 1–16.
EFSA, (European Food Safety Authority), 2011. Statement on tolerable weekly intake for cadmium. EFSA J. 9, 1975.
EFSA, (European Food Safety Authority), 2010. Panel on contaminants in the food chain (CONTAM). EFSA J. 8, 1570.
Endo, T., Hisamichi, Y., Haraguchi, K., Kato, Y., Ohta, C., Koga, N., 2008. Hg, Zn and Cu levels in the muscle and liver of tiger sharks (Galeocerdo cuvier) from the coast of Ishigaki Island, Japan: relationship between metal concentrations and body length. Mar. Pollut. Bull. 56, 1774–1780.
Fátima, W., Tojo, N., Ramzi, A., Somoue, L., Manchih, K., Errhif, A., 2015. Seasonal and size-dependent variability in diet of Scomber colias (Gmelin, 1789) of the Atlantic Coast of the Northwest Africa. Int. J. Adv. Res. 3, 485–497.
Ferreira, I., Gomes-Bispo, A., Lourenço, H., Matos, J., Afonso, C., Cardoso, C., Castanheira, I., Motta, C., Prates, J.A.M., Bandarra, N.M., 2020. The chemical composition and lipid profile of the chub mackerel (Scomber colias) show a strong

seasonal dependence: contribution to a nutritional evaluation. Biochimie 178, 181–189.
Frontalini, F., Coccioni, R., 2008. Benthic foraminifera for heavy metal pollution monitoring: a case study from the central Adriatic Sea coast of Italy. Estuar. Coast Shelf Sci. 76, 404–417.
Guerriero, G., Samah, M., Bassem, F.KhA.-G., 2018. Biological responses of white sea bream (Diplodus sargus, Linnaeus 1758) and sardine (sardine pilchardus, Walbaum 1792) exposed to heavy metal contaminated water. Emir. J. Food Agric. 30. https://doi.org/10.9755/ejfa.2018.v30.i8.1762.
Gushchin, A.V., Corten, A., 2017. Feeding of pelagic fish in waters of Mauritania: 3.—Atlantic Chub mackerel Scomber colias, Atlantic horse mackerel Trachurus trachurus, Cunene horse mackerel Trachurus trecae. J. Ichthyol. 57, 410–423.
Hakanson, L., 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. Water Res. 14, 975–1001.
Heithaus, M.R., Vaudo, J.J., 2004. Predator-prey interactions. Biology of sharks and their relatives 17, 487–521.
Hwang, D.-W., Kim, P.-J., Kim, S.-G., Sun, C.-I., Koh, B.-S., Ryu, S.-O., Kim, T.-H., 2019. Spatial distribution and pollution assessment of metals in intertidal sediments, Korea. Environ. Sci. Pollut. Control Ser. 26, 19379–19388.
Jakimska, A., Konieczka, P., Skóra, K., Namieśnik, J., 2011. Bioaccumulation of metals in tissues of marine animals, part I: the role and impact of heavy metals on organisms. Pol. J. Environ. Stud. 20.
Javed, M., Usmani, N., 2013. Assessment of heavy metal (Cu, Ni, Fe, Co, Mn, Cr, Zn) pollution in effluent dominated rivulet water and their effect on glycogen metabolism and histology of Mastacembelus armatus. SpringerPlus 2, 1–13.
Jesus, G.T., 1992. Study of the Growth and Reproduction of Trachurus picturatus (Bowdich, 1825) in Madeira. Doc. N. XIV/C/1-1991/03 (DGXIV/CE).
Jurado-Ruzafa, A., Sotillo-de-Olano, M.B., Hernández-Rodríguez, E.M., Santana, Z., González-Lorenzo, J.G., Perales-Raya, C., 2021. The Atlantic Chub Mackerel (Scomber colias) in the Canary Islands (Spain): fishery and Biological data Update. Centro Oceanográfico de Canarias.
Karimi, R., Chen, C.Y., Folt, C.L., 2016. Comparing nearshore benthic and pelagic prey as mercury sources to lake fish: the importance of prey quality and mercury content. Sci. Total Environ. 565, 211–221.
Keč, V.Č., Zorica, B., 2013. Length–weight relationship, age, growth and mortality of Atlantic chub mackerel Scomber colias in the Adriatic Sea. J. Mar. Biol. Assoc. U. K. 93, 341–349.
Khan, N., Jeong, I.S., Hwang, I.M., Kim, J.S., Choi, S.H., Nho, E.Y., Choi, J.Y., Kwak, B.-M., Ahn, J.-H., Yoon, T., Kim, K.S., 2013. Method validation for simultaneous determination of chromium, molybdenum and selenium in infant formulas by ICP-OES and ICP-MS. Food Chem. 141, 3566–3570. https://doi.org/10.1016/j.foodchem.2013.06.034.
Kime, D.E., 1995. The effects of pollution on reproduction in fish. Rev. Fish Biol. Fish. 5, 52–95.
Kraemer, L.D., Evans, D., Dillon, P.J., 2012. The impacts of ontogenetic dietary shifts in yellow perch (Perca flavescens) on Zn and Hg accumulation. Ecotoxicol. Environ. Saf. 78, 246–252.
Kumar, M., Gupta, N., Ratn, A., Awasthi, Y., Prasad, R., Trivedi, A., Trivedi, S.P., 2020. Biomonitoring of heavy metals in river ganga water, sediments, plant, and fishes of different trophic levels. Biol. Trace Elem. Res. 193, 536–547.
Lall, S.P., Kaushik, S.J., 2021. Nutrition and metabolism of minerals in fish. Animals 11, 2711.
Le Croizier, G., Schaal, G., Gallon, R., Fall, M., Le Grand, F., Munaron, J.-M., Rouget, M.-L., Machu, E., Le Loc'h, F., Laë, R., 2016a. Trophic ecology influence on metal bioaccumulation in marine fish: inference from stable isotope and fatty acid analyses. Sci. Total Environ. 573, 83–95.
Le Croizier, G., Schaal, G., Gallon, R., Fall, M., Le Grand, F., Munaron, J.-M., Rouget, M.-L., Machu, E., Le Loc'h, F., Laë, R., 2016b. Trophic ecology influence on metal bioaccumulation in marine fish: inference from stable isotope and fatty acid analyses. Sci. Total Environ. 573, 83–95.
Lens, P., Grotenhuis, T., Malina, G., Tabak, H., 2005. Soil and Sediment Remediation. IWA Publishing.
Lorenzo Nespereira, J.M., 1992. Crecimiento de la caballa "Scomber japonicus" (Houttuyn, 1872) en aguas del Archipiélago Canario. Universidad de Las Palmas de Gran Canaria.
Lozano-Bilbao, E., Delgado-Suárez, I., Lorenzo, J.M., González, J.A., Hardisson, A., González-Weller, D., Paz, S., Rubio, C., Gutiérrez, Á.J., 2024a. Metal variability in small pelagic fish Scomber colias as influenced by volcanic events in the Canary Islands. Environ. Sci. Pollut. Control Ser. 31, 49800–49810. https://doi.org/10.1007/s11356-024-34530-0.
Lozano-Bilbao, E., Delgado-Suárez, I., Paz-Montelongo, S., Hardisson, A., Pascual-Fernández, J.J., Rubio, C., Weller, D.G., Gutiérrez, Á.J., 2023. Risk assessment and characterization in tuna species of the Canary Islands according to their metal content. Foods 12, 1438.
Lozano-Bilbao, E., Jurado-Ruzafa, A., Lorenzo, J.M., González, J.A., Hardisson, A., González-Weller, D., Paz, S., Rubio, C., Gutiérrez, Á.J., 2024b. Environmental factors influencing metal concentrations in Scomber colias along the Canary Islands. Biol. Trace Elem. Res. https://doi.org/10.1007/s12011-024-04250-0.
Lozano-Bilbao, E., Lozano, G., Jiménez, S., Jurado-Ruzafa, A., Hardisson, A., Rubio, C., Weller, D.-G., Paz, S., Gutiérrez, Á.J., 2020. Seasonal and ontogenic variations of metal content in the European pilchard (Sardina pilchardus) in northwestern African waters. Environ. Pollut. 266, 115113. https://doi.org/10.1016/j.envpol.2020.115113.
Luoma, S.N., Carter, J.L., 2020. Effects of trace metals on aquatic benthos. In: Metal Ecotoxicology Concepts and Applications. CRC Press, pp. 261–300.
Madigan, D.J., Snodgrass, O.E., Fisher, N.S., 2018. From migrants to mossbacks: tracer- and tag-inferred habitat shifts in the California yellowtail Seriola dorsalis. Mar. Ecol. Prog. Ser. 597, 221–230.
Martins, M.M., Skagen, D., Marques, V., Zwolinski, J., Silva, A., 2013. Changes in the abundance and spatial distribution of the Atlantic chub mackerel (Scomber colias) in the pelagic ecosystem and fisheries off Portugal. Sci. Mar. 77, 551–563.
Mason, R.P., Laporte, J.-M., Andres, S., 2000. Factors controlling the bioaccumulation of Mercury, methylmercury, arsenic, selenium, and cadmium by freshwater invertebrates and fish. Arch. Environ. Contam. Toxicol. 38, 283–297. https://doi.org/10.1007/s002449910038.
Matloff, N., 2011. The Art of R Programming: a Tour of Statistical Software Design. No Starch Press.
Maz-Courrau, A., López-Vera, C., Galván-Magaña, F., Escobar-Sánchez, O., Rosíles-Martínez, R., Sanjuán-Muñoz, A., 2012. Bioaccumulation and biomagnification of total Mercury in four exploited shark species in the Baja California Peninsula, Mexico. Bull. Environ. Contam. Toxicol. 88, 129–134. https://doi.org/10.1007/s00128-011-0499-1.
Menezes, G.M., Sigler, M.F., Silva, H.M., Pinho, M.R., 2006. Structure and zonation of demersal fish assemblages off the Azores Archipelago (mid-Atlantic). Mar. Ecol. Prog. Ser. 324, 241–260.
Mille, T., Cresson, P., Chouvelon, T., Bustamante, P., Brach-Papa, C., Bruzac, S., Rozuel, E., Bouchoucha, M., 2018. Trace metal concentrations in the muscle of seven marine species: comparison between the Gulf of Lions (North-West Mediterranean Sea) and the Bay of Biscay (North-East Atlantic Ocean). Mar. Pollut. Bull. 135, 9–16.
Mziray, P., Kimirei, I.A., 2016. Bioaccumulation of heavy metals in marine fishes (Siganus sutor, Lethrinus harak, and Rastrelliger kanagurta) from Dar es Salaam Tanzania. Reg. Stud. Mar. Sci. 7, 72–80.
Navarro, M.R., Villamor, B., Myklevoll, S., Gil, J., Abaunza, P., Canoura, J., 2012. Maximum size of Atlantic mackerel (Scomber scombrus) and Atlantic chub mackerel (Scomber colias) in the Northeast Atlantic. Cybium (Paris) 36, 406–408.
Oros, A., 2025. Bioaccumulation and trophic transfer of heavy metals in marine fish: ecological and ecosystem-level impacts. J. Xenobiot. 15, 59.
Parietti, M., Giorgini, M., Orlando, P., Derisio, C., Temperoni, B., Padovani, L.N., Marrari, M., Buratti, C.C., 2025. Beyond the boundaries: poleward range expansion of the Atlantic chub mackerel Scomber colias in SW Atlantic Ocean. Fish. Oceanogr. 34, e12711.
Perugini, M., Visciano, P., Manera, M., Zaccaroni, A., Olivieri, V., Amorena, M., 2014. Heavy metal (As, Cd, Hg, Pb, Cu, Zn, Se) concentrations in muscle and bone of four commercial fish caught in the central Adriatic Sea, Italy. Environ. Monit. Assess. 186, 2205–2213.
Pryor, L.J.E., Casto, J.M., 2017. Ectoparasites as developmental stressors: effects on somatic and physiological development. J. Exp. Zool. A Ecol. Integr. Physiol. 327, 311–321.
Rahman, A.N.A., ElHady, M., Hassanin, M.E., Mohamed, A.A.-R., 2019. Alleviative effects of dietary Indian lotus leaves on heavy metals-induced hepato-renal toxicity, oxidative stress, and histopathological alterations in Nile tilapia, Oreochromis niloticus (L.). Aquaculture 509, 198–208.
Rainbow, P.S., 2007. Trace metal bioaccumulation: models, metabolic availability and toxicity. Environ. Int. 33, 576–582.
Ramos-Miras, J.J., Sanchez-Muros, M.J., Morote, E., Torrijos, M., Gil, C., Zamani-Ahmadmahmoodi, R., Martin, J.A.R., 2019. Potentially toxic elements in commonly consumed fish species from the western Mediterranean Sea (Almería Bay): bioaccumulation in liver and muscle tissues in relation to biometric parameters. Sci. Total Environ. 671, 280–287. https://doi.org/10.1016/j.scitotenv.2019.03.359.
R-Core Team, 2025. R: a language and Environment for Statistical Computing, R. R Foundation for Statistical Computing.
Rivas-Mena, G., Sánchez-Guerrero-Hernández, M.J., Yeste, M.P., Ramos, F., González-Ortegón, E., 2024. Microplastics in the stomach content of the commercial fish species Scomber colias in the Gulf of Cadiz, SW Europe. Mar. Pollut. Bull. 200, 116049.
Ryu, J., Khim, J.S., Kang, S.-G., Kang, D., Lee, C., Koh, C., 2011. The impact of heavy metal pollution gradients in sediments on benthic macrofauna at population and community levels. Environ. Pollut. 159, 2622–2629.
Saidon, N.B., Szabó, R., Budai, P., Lehel, J., 2024. Trophic transfer and biomagnification potential of environmental contaminants (heavy metals) in aquatic ecosystems. Environ. Pollut. 340, 122815.
Sánchez-Hernández, J., Nunn, A.D., Adams, C.E., Amundsen, P., 2019. Causes and consequences of ontogenetic dietary shifts: a global synthesis using fish models. Biol. Rev. 94, 539–554.
Sbiba, S.E., Correia, A.T., Nikolioudakis, N., Bazairi, H., Chlaida, M., 2024. Insights into the stock structure of Scomber colias Gmelin, 1789 along the Northwest African coast inferred from otolith shape analysis. Fish. Res. 272, 106955.
Scavetta, R., Angelov, B., 2021. Python and R for the Modern Data Scientist. O'Reilly Media, Incorporated.
Scott, M.D., Chivers, S.J., Olson, R.J., Fiedler, P.C., Holland, K., 2012. Pelagic predator associations: tuna and dolphins in the eastern tropical Pacific Ocean. Mar. Ecol. Prog. Ser. 458, 283–302.
Silva, A.G., Martinez, C.B.R., 2007. Morphological changes in the kidney of a fish living in an urban stream. Environ. Toxicol. Pharmacol. 23, 185–192.
Stillman, M.J., 1995. Metallothioneins. Coord. Chem. Rev. 144, 461–511.
Taylor, J.J., Rytwinski, T., Bennett, J.R., Smokorowski, K.E., Lapointe, N.W.R., Janusz, R., Clarke, K., Tonn, B., Walsh, J.C., Cooke, S.J., 2019. The effectiveness of spawning habitat creation or enhancement for substrate-spawning temperate fish: a systematic review. Environ. Evid. 8, 19.
Tsui, M.T.K., Finlay, J.C., Nater, E.A., 2009. Mercury bioaccumulation in a stream network. Environ. Sci. Technol. 43, 7016–7022.

Tvermoes, B.E., Paustenbach, D.J., Kerger, B.D., Finley, B.L., Unice, K.M., 2015. Review of cobalt toxicokinetics following oral dosing: implications for health risk assessments and metal-on-metal hip implant patients. Crit. Rev. Toxicol. 45, 367–387. https://doi.org/10.3109/10408444.2014.985818.

Tyler, G., Yvon, J., 1995. ICP-OES, ICP-MS and AAS techniques compared. ICP Optical Emission Spectroscopy Technical Note 5.

Valente, T., Costantini, M.L., Ventura, D., Careddu, G., Ciaralli, L., Monfardini, E., Tomassetti, P., Piermarini, R., Silvestri, C., Matiddi, M., 2025. Hit the target: a new experimental method to select bioindicators of microplastic ingestion by marine fish. Environ. Res., 120940

Velasco, E.M., Árbol-Pérez, J.P. del, Baro, J., Sobrino, I., 2011. Age and growth of the Spanish chub mackerel Scomber colias off southern Spain: a comparison between samples from the NE Atlantic and the SW Mediterranean. Centro Oceanográfico de Gijón.

Villamor, B., Carrera, P., Castro, J., Ramos, F., Velasco, F., Sobrino, I., Navarro, M.R., Gancedo, R.M., Hernández, C., Marín, M., 2017a. The Chub Mackerel (Scomber colias) in the Atlantic Spanish Waters (ICES divisions 8. c and 9. a): biological, fishery and survey data. Centro Oceanográfico de Santander.

Villamor, B., Carrera, P., Castro, J., Ramos, F., Velasco, F., Sobrino, I., Navarro, M.R., Gancedo, R.M., Hernández, C., Marín, M., 2017b. The Chub Mackerel (Scomber colias) in the Atlantic Spanish Waters (ICES divisions 8. c and 9. a): biological, fishery and survey data. Centro Oceanográfico de Santander.

Younis, A.M., Amin, H.F., Alkaladi, A., Mosleh, Y.Y.I., 2015. Bioaccumulation of heavy metals in fish, squids and crustaceans from the Red Sea, Jeddah Coast, Saudi Arabia. Open J. Mar. Sci. 5, 369.