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INTERANNUAL VARIATION IN LENGTH STRUCTURE AND REPRODUCTIVE CONTRIBUTION OF *Alosa immaculata* IN THE BLACK SEA-DANUBE SYSTEM (2020-2025)

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Abstract

An anadromous keystone species in the Black Sea-Danube system, Alosa immaculata plays an important ecological role by linking marine feeding habitats with riverine spawning grounds. Alterations in size structure can directly affect its reproductive output and long-term population stability. This work evaluates the interannual evolution (2020-2024) of length-frequency structure in Black Sea and Danube catches to assess changes in population composition, size-selective migration, and reproductive contribution. Marine data describe the feeding population, while riverine catches represent the spawning stock. Temporal comparisons focus on shifts in size spectra, variation in the proportion of sexually mature individuals, and persistence of the biological filter separating juvenile marine components from migrating adults. Results highlight consistent dominance of smaller size classes in the marine environment and the prevalence of mature individuals in riverine catches, with interannual variability in the representation of large size classes. These patterns indicate a stable but potentially vulnerable reproductive bottleneck, amplified by selective fishing during migration. Integrating multi-year marine and riverine length-based data supports assessment of population resilience and protection of mature individuals during reproduction.

Key words*: anadromous fish, interannual variability, length-frequency structure, pontic shad, size-selective migration, spawning stock dynamics.*

INTRODUCTION

The Pontic shad (*Alosa immaculata*) is an anadromous species of major ecological importance within the Black Sea–Danube system, contributing to the transfer of energy and nutrients between marine and freshwater ecosystems (Navodaru, 2001; Višnjić-Jeftić et al., 2013; Raikova-Petrova, 2013; Rozdina et al., 2015; Lenhardt et al., 2016; Grecu et al., 2020). Through its seasonal migration, downstream for juveniles and upstream for spawners, the species supports trophic connectivity and ecosystem functioning along the river-sea continuum (Țiganov et al., 2016; Leonov et al., 2022; 2023; Kirin et al., 2023).
Because individuals of different sizes use marine and riverine habitats unevenly throughout their life cycle, comparisons of length–frequency structure between habitats can provide insight into population connectivity across the Black Sea-Danube continuum. In anadromous fishes, size-dependent habitat use and migration timing are widely recognized mechanisms linking marine feeding areas to freshwater reproductive

habitats (Gross et al., 1988; Quinn & Myers, 2004; Secor, 2015). Accordingly, analysing size structure across habitats allows the evaluation of how demographic components are spatially distributed within this migratory system.

Connectivity between the Black Sea and the Danube system is a defining feature of the Pontic shad life cycle. Early juveniles drift seaward through the Danube Delta under the influence of river hydrology (Navodaru, 2001), subadults and adults exploit marine feeding habitats for growth, and sexually mature individuals migrate upstream to spawn. In many anadromous fishes, migration timing and river entry are influenced by size, age, and physiological condition (Quinn & Myers, 2004; Secor, 2015). In this context, analysing size structure across habitats provides a framework for exploring how different demographic components are distributed along the marine–freshwater continuum.

Owing to its complex life cycle, the Pontic shad is particularly vulnerable to anthropogenic pressures, including overfishing, habitat fragmentation, and hydrological alterations (Navodaru, 1996; Navodaru & Waldman, 2003; Višnjić-Jeftić et al., 2010; Smederevac-Lalić et al., 2018, Balik, 2019; Mocanu et al., 2020).

Body size is a key indicator of sexual maturity and reproductive contribution at the population level (Murua et al., 2003; Raikova-Petrova et al., 2013; Dobre et al., 2025) Length-frequency structure reflects both natural biological processes and the effects of external pressures and is therefore widely used to assess stock status. In Pontic shad, and differences between marine and riverine stock structures provide critical insight into biological selectivity and fishing impacts (Stroe et al., 2024).

Although previous studies have addressed interannual variation in length-frequency structure as central components of demographic assessments, with significant variation in cohort composition and sex ratio observed during reproductive migration in the Danube River (Nastase et al., 2018; Leonov et al., 2022; 2023), integrated comparisons between marine and riverine components remain limited. In particular, few studies have linked interannual changes in size structure to reproductive contribution within a unified analytical framework across habitats.

The present analysis focuses specifically on the marine feeding component (including juveniles, subadults, and adults present at sea prior to spawning migration) and on the upstream spawning component in the Danube River. It does not address downstream-drifting larvae or early juveniles within the riverine system. Therefore, the comparison targets size structure between the marine feeding assemblage and the riverine spawning assemblage, rather than across all life stages occurring within the river.

Interannual changes (2020-2025) in the length-frequency structure of Pontic shad are evaluated by integrating data from the Black Sea feeding grounds and the Danube River spawning migration. By jointly analysing marine and riverine components, the analysis aims to clarify population dynamics, assess the stability of the size-selective migration process, and explore the potential of marine length structure as an early structural indicator of subsequent spawning run composition in the Danube.

MATERIALS AND METHODS

Study area. The study was conducted within the Black Sea-Danube system, which represents a key ecological continuum for the life cycle of the Pontic shad (*Alosa immaculata*).

The Black Sea represents the main feeding and growth habitat for subadult and adult Pontic shad, where individuals accumulate energetic reserves prior to reproductive migration. The Danube River functions as the seasonal spawning migration corridor and reproductive habitat for mature individuals. This spatial structuring of life-history stages enables comparative assessment of size structure across feeding and spawning habitats within the migratory system. The study area represents a critical habitat for the species, functioning both as a spawning ground and a key migratory corridor.

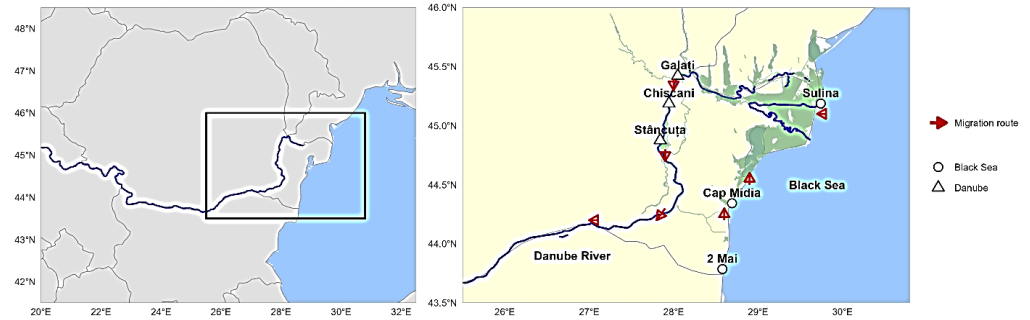

Figure 1. Study area (Source: original)

Data collection. Data were collected over a six-year period (2020-2025). Pontic shad specimens from the Danube River were obtained during scientific fishing surveys conducted by researchers from ICDEAPA Galați during the reproductive migration period, in the lower Danube sector, specifically in the areas of Galați, Chiscani, and Stâncuța. Marine data were collected by researchers from INCDM Constanța along the Romanian Black Sea coast, in the areas of 2 Mai, Cap Midia, and Sulina, corresponding to key coastal and nearshore habitats used by the species prior to spawning migration.

The Black Sea individuals were captured using fixed gillnets with a mesh size of 32-40 mm, a maximum net length of 100 m, a maximum net height of 8 m, and a twine diameter ranging from 0.2 to 0.3 mm, while the Danube River samples were captured using drift gillnets with a mesh size of 30-35 mm, as stated in Order 59/2021. The individuals were randomly selected to ensure the representation of individuals across all length classes. Total length (TL, cm) was measured with an ichthyometer, with an accuracy of 0.1 cm and sex was determined by gonadal inspection.

Length-frequency distributions were constructed using 1-cm class intervals. Class-based percentage frequencies were calculated separately for each year and habitat prior to statistical analyses.

Individuals in this study were classified as mature at a threshold length of 22 cm in the Black Sea. Pontic shad typically reaches sexual maturity at 2-3 years of age (Balik, 2019), corresponding to body lengths of approximately 20-30 cm (Stroe et al., 2021). The minimum legal retention size under current fisheries regulations is 22 cm (Order no. 304/2023). This threshold of 22 cm ensure consistency between biological interpretation and management practice, although actual maturity may vary within this size interval.

Statistical analyses. Length-frequency data were available as percentage distributions by 1-cm size classes for each year and habitat. Because individual-level observations were not available, proportional distributions were transformed into pseudo-individual datasets by replicating each class midpoint according to its reported percentage frequency. This reconstruction preserves the relative structure of the empirical distributions and allows application of distribution-based non-parametric tests that require individual-level input. The procedure represents an analytical transformation of proportional data and does not introduce additional biological information. Consequently, statistical inference focuses primarily on distributional divergence (K-S Dstatistic) rather than on absolute frequency-based significance levels.

Interannual variation in size structure was analysed separately for the marine and riverine components. Interannual and sex-specific length-frequency distributions were compared using the Kolmogorov-Smirnov test, a non-parametric method suitable for aggregated length-class data that evaluates differences in distributional shape and position and is widely applied in fisheries and population ecology when assumptions of normality and independence are not met (Sokal & Rohlf, 1995; Anderson & Neumann, 1996; Quinn & Deriso, 1999; Zar, 2010).

To account for multiple pairwise comparisons, p-values were adjusted using both false discovery rate (FDR) and Bonferroni corrections.

Interannual differences in the proportions of juvenile and mature individuals were assessed using the chi-square test, appropriate for categorical, frequency-based data with independent yearly groups (Sokal & Rohlf, 1995; Anderson & Neumann, 1996; Zar, 2010)

All statistical analysis were made using RStudio/2025.09.2+418.

To facilitate visual interpretation of modal structure in the length-frequency distributions, primary and secondary peaks were identified for each year based on the relative frequency of length classes. Using proportional length-frequency data, the two length classes with the highest percentages within each annual distribution were extracted. The class with the highest frequency was defined as the primary modal class, while the class with the second-highest frequency was considered the secondary modal class. These modal classes were used solely as descriptive indicators of distributional structure and were illustrated in the figures using dashed vertical lines. Because modal identification was based on aggregated proportional data, the resulting peaks represent the most prominent frequency classes rather than statistically validated local maxima.

Figures and maps. All figures were created using RStudio/2026.01.1+403 version.

RESULTS AND DISCUSSIONS

The size composition of Pontic shad catches differed between the Black Sea and the Danube River and varied among years between 2020 and 2025. In the Black Sea, captured individuals covered a wide range of total lengths, from 17 to 38 cm, with most of the catch consistently concentrated between 26 and 33 cm across years. The highest relative frequencies were generally observed in the 28-31 cm length classes, particularly in 2021-2023. Similar mean body sizes were reported for Pontic shad in the Black Sea by Tiganov et al. (2016), who observed an average total length of approximately 30.7 cm in commercial catches, while a comparable length range (18-36 cm) was previously documented in 2013 (Tiganov et al., 2013). For the Turkish part of the Black Sea, the maximum length in catches was 34.2 cm for *A. immaculata* (Erguden et al., 2011).

In the Danube River, catches were more restricted to larger size classes, with individuals ranging between 25 and 36 cm. Length classes below 23 cm were absent or rare in most years. The modal length classes were typically between 28 and 32 cm, with a pronounced contribution of larger individuals in several years, especially from 2020 onwards. For instance, Grecu et al. (2020) reported length classes ranging from 29 to 34.5 cm in 2020, whereas Ibănescu et al. (2017) documented a broader size spectrum, spanning 24-39 cm. For the Bulgarian sector of the Danube River, Kirin et al. (2023) found a maximum length in captures of 30 cm.

Sex composition of Pontic shad catches showed interannual variability in both study areas between 2020 and 2025 (Table 1). In the Black Sea, females generally represented a higher proportion of the annual samples, accounting for 49.4-64.2% of individuals in most years, except for 2022, when males predominated (56.0%). A female-dominated sex structure in Romanian Black Sea catches was also reported by Tiganov et al. (2016). In the Danube River, females also tended to be more abundant, representing between 50.9% and 64.2% of the catches, while males accounted for 35.8-49.1%. Same female predominance was reported also by Leonov et al. (2022) in 2022

Table 1. Sex composition (%) of Pontic shad catches by study area (Black Sea and Danube River) and year (2020-2025)

Area	Black Sea	Black Sea	Black Sea	Black Sea	Black Sea	Black Sea	Danube	Danube	Danube	Danube	Danube	Danube
Year	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
F	54.76	56.18	44.00	49.42	58.15	64.18	53.73	52.48	58.82	50.89	55.54	64.24
M	45.24	43.82	56.00	50.58	41.85	35.82	46.27	47.52	41.18	49.11	44.46	35.76
	100	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

The predominance of females observed in both marine and riverine catches likely reflects a combination of biological and methodological factors. Sexual size dimorphism in Pontic shad, with females typically attaining larger body sizes (Navodaru, 2001; Năstase, 2018; Leonov et al., 2022), increases their probability of retention in gillnets targeting commercial size classes (Hamley, 1975; Millar & Mainguy, 2025). In marine habitats, sex-specific spatial distribution or differences in feeding intensity may further influence capture rates. During spawning migration in the Danube River, the female-biased structure may additionally reflect differential reproductive investment, as fecundity in clupeid fishes increases with body size and larger females contribute disproportionately to reproductive output (Dobre et al., 2025).

Size-dependent participation in migration has been widely described in anadromous fishes (Quinn & Myers, 2004; Secor, 2015). Together, these biological characteristics, combined with gear selectivity, likely explain the recurrent female dominance across habitats. Across both study areas, the relative contribution of sexes fluctuated among years.

Size structure of the Black Sea component

The Black Sea represents the primary feeding and growth habitat of Pontic shad, where population structure reflects the combined effects of recruitment variability, growth processes, and migratory dynamics. Accordingly, the size structure of the marine component provides insight into interannual changes in cohort composition prior to spawning migration.

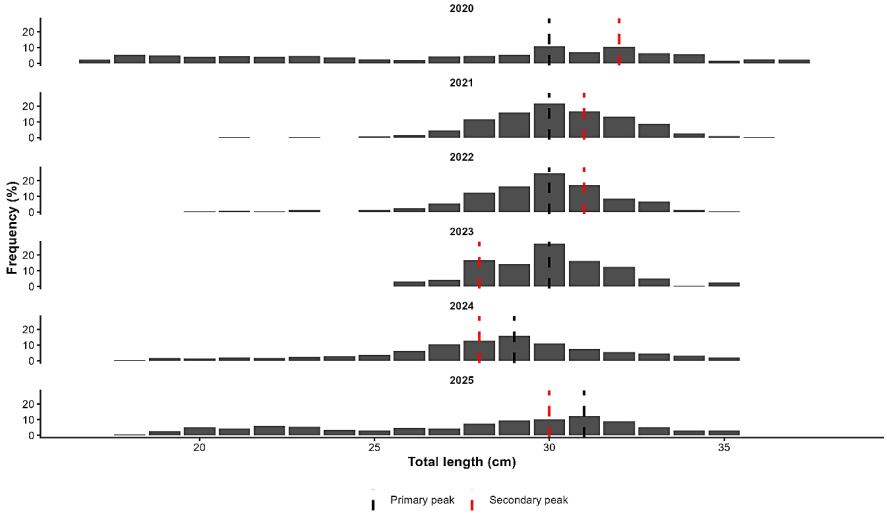

Figure 2. Length-frequency structure of Pontic shad in the Black Sea by year (Source: original)

Figure 2 illustrates pronounced interannual variation in the length-frequency distributions of Pontic shad within the Black Sea feeding component between 2020 and 2025. The vertical arrangement facilitates direct comparison of modal displacement across consecutive years, allowing visual inspection of potential cohort progression.

The 2020 distribution is relatively broad and includes a higher contribution of smaller size classes, as evidenced by the extended left tail of the histogram and the presence of a secondary peak below the dominant modal class around 29-31 cm. In that year, length classes below approximately 26-27 cm contribute noticeably higher proportions compared to subsequent years, resulting in a wider overall spread of the distribution. In contrast, distributions observed during 2021-2023 are more concentrated and dominated by intermediate to larger individuals, suggesting a phase of relative structural stability and modal consolidation around 29-31 cm.

The distributions recorded in 2024 and particularly in 2025 appear more dispersed and partially shifted toward smaller size classes,

indicating renewed variability in cohort representation in the most recent years.

Interannual variability is also evident in the relative prominence and position of secondary peaks, indicating fluctuations in cohort representation. In the figure, dashed vertical lines indicate the primary and secondary modal classes, defined as the length classes with the highest and second-highest frequencies, respectively; their relative position along the length axis may vary among years depending on cohort composition**.** Although these modal shifts may suggest cohort progression, confirmation would require age-based data.

These visual patterns are strongly supported by the Kolmogorov-Smirnov analysis, which detected highly significant differences in length-frequency distributions across all interannual comparisons. Biological interpretation should therefore focus primarily on the magnitude and temporal pattern of K-S Dstatistic values rather than on p-values alone, given the large pseudo-sample sizes used to represent proportional data.

Large effect sizes between 2020 and 2021-2023, as well as between 2025 and all preceding years, point to major structural shifts in population composition, while comparatively lower D values among 2021-2023 indicate a phase of relative stability in the Black Sea stock. Consistent with these results, the chi-square analysis revealed significant interannual variation in the relative proportions of juvenile and mature individuals, further supporting the presence of marked temporal variability in size structure rather than a static demographic pattern. Taken together, the concordant outcomes of distribution-based (K-S) and proportion-based (χ^2) analyses indicate that the Black Sea feeding component exhibits year-specific variability in cohort composition. These differences are best interpreted as interannual fluctuations in size structure rather than as evidence of long-term demographic change.

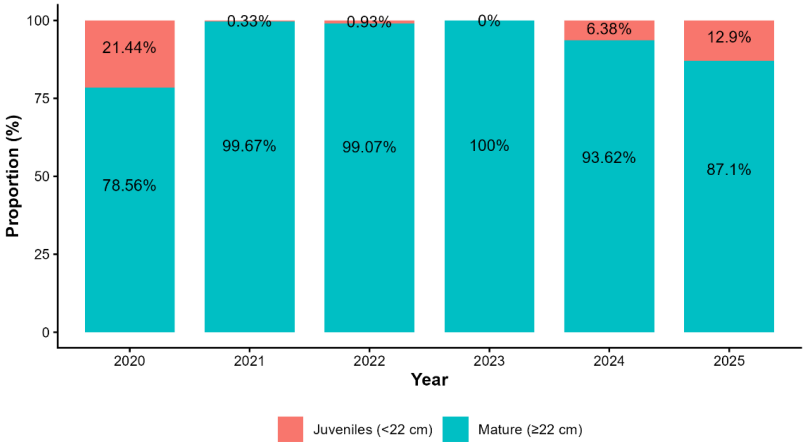

Figure 3. Interannual variation in the proportion of juvenile and mature Pontic shad in the Black Sea (Source: original)

In addition to distributional shape and central tendency, interannual changes in size structure within the Black Sea feeding component are further illustrated by the relative contribution of juvenile and mature individuals (Figure 3). The stacked bar chart shows pronounced interannual variability in the proportion of juveniles (<22 cm) and mature individuals (≥22 cm), a pattern that is statistically supported by the chi-square test, which detected highly significant differences among years (χ^2 = 5748.2, df = 5, $p < 0.001$). Standardized residuals indicate a higher-than-expected contribution of juveniles in 2020 and 2025, whereas the period 2021–2023 was characterized by an overwhelming predominance of mature individuals.

Years dominated by mature individuals (2021-2023) coincide with relatively concentrated length-frequency distributions, suggesting a phase of cohort progression and dominance of larger size classes within the marine feeding

assemblage. In contrast, the increased juvenile contribution observed in 2020 and especially in 2025 corresponds to broader distributions, indicating a greater relative presence of smaller size classes during these years.

Although the Black Sea represents the primary feeding and growth area for Pontic shad, persistent juvenile dominance is not expected, as early life stages primarily occupy coastal and nearshore habitats and are typically underrepresented in offshore samples. Additionally, gear selectivity may further reduce the capture probability of smaller individuals, as gillnets retain fish within specific size ranges determined by mesh size (Tiganov et al., 2022). Consequently, the low proportion of juveniles in marine samples likely reflects both ontogenetic habitat segregation and methodological constraints. Consequently, the observed interannual fluctuations in juvenile contribution likely reflect variability in recruitment strength, timing of offshore habitat use, and migration dynamics, rather than a fixed ecological pattern. Collectively, the concordant outcomes of the chi-square analysis, distribution-based comparisons (K-S), reinforce the interpretation that the marine feeding component exhibits dynamic, year-specific cohort composition, emphasizing the importance of interannual perspectives when evaluating population structure and demographic processes in the Black Sea-Danube system.

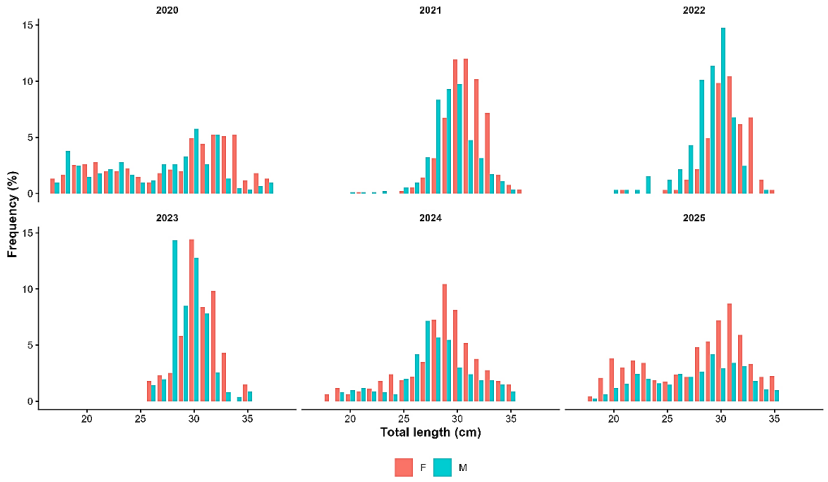

Figure 4. Sex-specific length-frequency distributions of Pontic shad by year in the Black Sea (Source: original)

Sex-specific patterns in size structure within the Black Sea feeding component are illustrated in Figure 4, which shows female and male length-frequency distributions for each year between 2020 and 2025. Visual inspection of the histograms indicates consistent differences in distributional shape, modal length, and spread between sexes, although the degree of overlap varies among years. In several years (notably 2021-2023), females and males exhibit partially distinct modal classes, whereas in other years (e.g., 2025) their distributions appear more similar, suggesting higher overlap in size composition.

Overall, these results indicate persistent but temporally variable sex-related differences in size structure within the marine feeding assemblage. Such differences may reflect sex-specific growth trajectories, differential habitat use, or variation in migration timing between females and males, although these interpretations remain indicative given the aggregated nature of the data. The consistently strong statistical significance across years highlights the sensitivity of distribution-based methods applied to large pseudo-samples derived from length-class frequencies.

Interannual variability in size structure within the Black Sea feeding component highlights the role of migratory selectivity in shaping marine assemblages. The predominance of larger individuals suggests that the Black Sea

functions primarily as a feeding and growth habitat for subadult and adult Pontic shad, whereas early juveniles are more frequently associated with shallow coastal and delta-influenced habitats, leading to their reduced representation in offshore samples. Consequently, the marine size structure does not represent a random cross-section of the population but reflects selective habitat use linked to ontogenetic stage and migration timing.

The reproductive structure inferred from the marine component suggests that temporal shifts in size composition are more likely driven by interannual variation in cohort representation and migration timing than by abrupt changes in the overall abundance of spawning individuals. Across all years, a consistent modal peak around 29-31 cm is observed, indicating the persistent presence of a dominant subadult/adult cohort in the marine feeding component. Periods characterized by higher relative juvenile contribution reflect the additional presence of smaller size classes superimposed on this stable modal structure, rather than a replacement of the larger cohort. These fluctuations therefore suggest variability in cohort representation rather than shifts in overall size dominance.

These patterns underscore the importance of interpreting marine size distributions within the context of the Black Sea-Danube migratory continuum, rather than as standalone indicators of reproductive potential.

Size structure of the Danube River component

In contrast to the marine feeding component, the Danube River represents the reproductive migration corridor of Pontic shad, where size structure is shaped by maturation selectivity and spawning-related processes rather than by recruitment or feeding dynamics. The ecological importance of the lower Danube and its distributaries as selective reproductive habitats have been extensively documented for anadromous fishes (Lenhardt et al., 2006; Danalache et al., 2017).

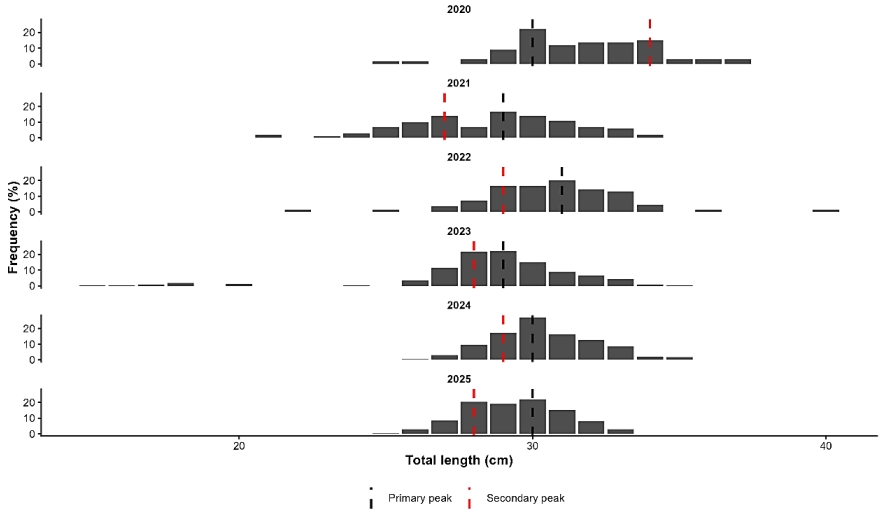

Figure 5. Length-frequency structure of Pontic shad in the Danube River by year (Source: original)

The annual length-frequency histograms for the Danube component (Figure 5) reveal clear interannual variation in modal structure and dispersion. For example, spawning seasons 2022 and 2024 are visually dominated by intermediate size classes (~28-31 cm), where the primary modal peak is sharply defined and frequencies are concentrated within a relatively narrow range. In contrast, 2020, 2021, and 2025 display broader distributions with increased representation of both smaller and larger individuals, resulting in a wider spread of the histogram and the appearance of secondary peaks. These features indicate the

simultaneous presence of multiple size cohorts within the spawning assemblage during those years. In the figure, dashed vertical lines mark the primary and secondary modal classes, corresponding to the length classes with the highest and second-highest frequencies within each annual distribution.

These visual differences are quantitatively supported by Kolmogorov-Smirnov comparesons, which detected significant distributional divergence between all year pairs (adjusted $p < 0.001$). The largest effect sizes (K-S D statistic) were observed between structurally contrasting years, such as 2020-2023 (D = 0.488) and 2020-2025 (D = 0.393), reflecting pronounced shifts in distributional shape. Conversely, lower D values between more similar years (e.g., 2024-2025: D = 0.196) indicate partial structural overlap. Together, the concordance between histogram patterns and D statistics demonstrates substantial interannual variability in the size structure of the Danube spawning population.

Across all analyzed years (2020-2025), the Kolmogorov-Smirnov test revealed large and highly significant differences between female and male length distributions (D = 0.41-0.62, $p_adj < 0.001$), confirming persistent sexual size dimorphism within the spawning population. Females consistently dominated larger size classes (~29-33 cm), whereas males were more frequently concentrated in slightly smaller ranges (~26-30 cm), with limited overlap.

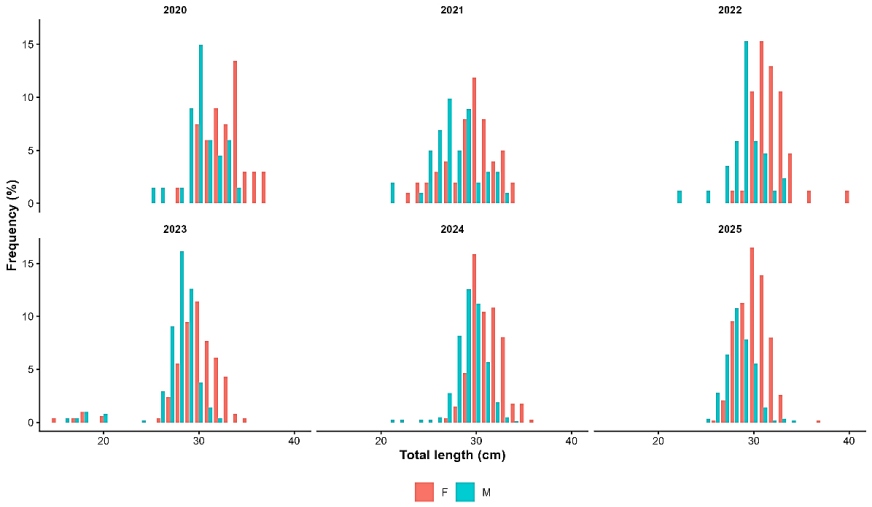

Figure 6. Sex-specific length-frequency distributions of Pontic shad by year in the Danube River (Source: original)

Importantly, interannual shifts in modal structure are evident within both sexes (Figure 6), indicating that year-to-year variability is not merely a consequence of sex aggregation but reflects genuine changes in cohort representation. Thus, the combined analysis captures overall demographic structure, while sex-specific patterns confirm a stable size hierarchy characteristic of the reproductive component.

Together, these results may indicate that the Danube River component reflects a biologically coherent reproductive assemblage, in which females attain larger sizes than males, consistent with differential energetic allocation to gonadal development and reproductive output. The concordance between statistical tests, and graphical patterns may underscore a robust and temporally stable biological signal, rather than sampling or methodological artifacts.

Conceptual framework linking marine feeding and riverine reproductive components of Pontic shad through size-selective migration in the Black Sea-Danube system

Figure 7 synthesizes this relationship conceptually, illustrating how size structure emerging from the marine feeding component is selectively transferred to the riverine reproductive habitat through spawning migration.

This framework is consistent with ecological models describing anadromous fishes as vectors linking marine feeding habitats to freshwater reproduction, thereby coupling energy flow and demographic processes across ecosystems (Gross et al., 1988; MacAvoy et al., 2009; Dodson et al., 2013).

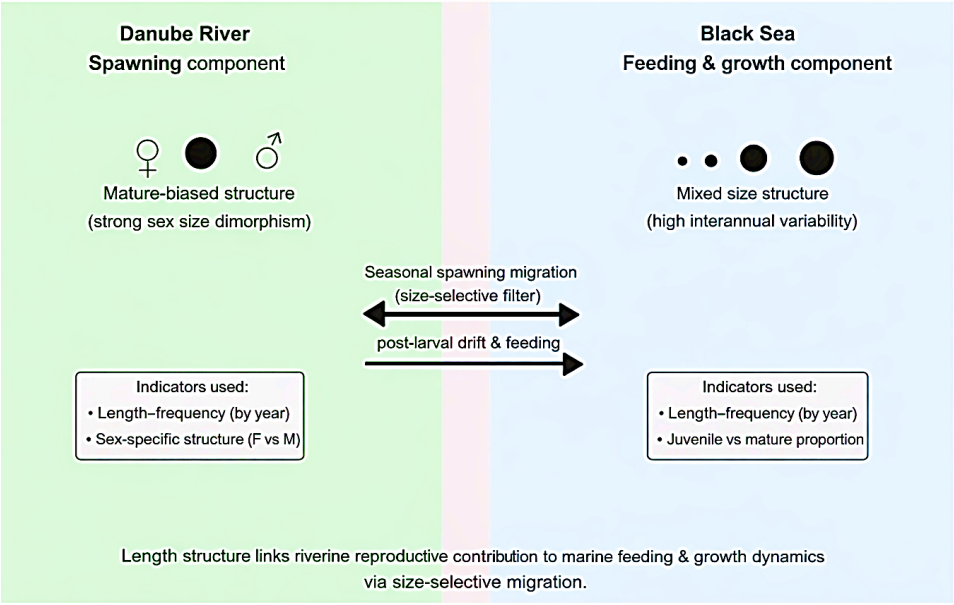

Figure 7. Length structure integrating marine feeding dynamics with riverine reproductive contribution through size-selective migration (Source: original)

Anadromous migration is widely interpreted as an adaptive strategy coupling productive marine feeding habitats with freshwater reproductive environments, mediated by size- and condition-dependent migratory decisions (Dodson et al., 2013; Schindler et al., 2015; Secor, 2015).

Within this continuum, participation in reproductive migration functions as a biologically selective process, whereby larger and sexually mature individuals exhibit a higher probability of upstream movement, particularly females. This size- and sex-dependent participation pattern has been widely documented for Pontic shad and other anadromous clupeids (Navodaru, 2001; Raikova-Petrova, 2013; Lenhardt et al., 2016; Năstase et al., 2018; Leonov et al., 2022; Quinn & Myers, 2004; Secor, 2015).

In this context, the size structure observed in the Black Sea may function as an upstream demographic signal that, after a maturation lag and size-selective migration, is progressively translated into the structure of the spawning population in the Danube. Pontic shad typically reaches sexual maturity at approximately 2-3 years of age (Navodaru, 2001; Raikova-Petrova, 2013; Lenhardt et al., 2016), implying that size cohorts observed in the marine feeding grounds may contribute to the spawning migration after a temporal lag. Consequently, fluctuations in marine length structure may contain predictive information regarding the composition of subsequent spawning runs. However, confirming such anticipatory capacity would require quantitative indicators of abundance (e.g., standardized CPUE) in both marine and riverine components, which were beyond the scope of the present study (Anderson & Neumann, 1996; Quinn & Deriso, 1999; Shin et al., 2005).

Research limitations

Several limitations should be acknowledged. The analyses were based on aggregated length–frequency data rather than individual-level measurements, and interpretations therefore reflect population-level structure rather than

individual growth trajectories or reproductive status. In addition, sampling reflects the inherent size selectivity of fishing gear and monitoring programs and may underrepresent early life stages or nearshore components of the population. However, this limitation primarily affects the representation of smaller size classes within each habitat and does not account for the consistent differences observed between the marine and riverine components, which are more plausibly explained by biological processes related to maturation and migration.

Finally, environmental drivers and fishing effort were not explicitly modelled, limiting inference on causal mechanisms underlying the observed variability.

The study focused on structural indicators and did not include standardized abundance indices (e.g., CPUE or biomass estimates), limiting inference regarding absolute changes in spawning stock size or recruitment magnitude. Age determination was not conducted; consequently, cohort progression is inferred from modal displacement rather than validated through age-structured analysis. The six-year time series may also be insufficient to detect longer-term demographic cycles. Additionally, hydrological drivers and fishing effort were not explicitly modelled, although they likely contribute to observed variability. Finally, the reconstruction of pseudo-individual datasets from proportional data may influence nominal statistical power; therefore, interpretation emphasizes effect sizes and distributional patterns rather than p-values alone.

CONCLUSIONS

This study provides an integrated assessment of interannual variability in the size structure of Pontic shad (*Alosa immaculata*) across the Black Sea-Danube system, highlighting the value of size-based metrics for linking marine feeding dynamics with riverine reproductive contribution. Analyses of length-frequency distributions and juvenile-mature proportions, consistently revealed pronounced year-specific variability in the marine feeding component, rather than a monotonic trend over the 2020-2025 period.

The Black Sea component was characterized by dynamic cohort representation, with significant interannual shifts in distributional shape and size composition. In contrast, the Danube River component displayed a more selectively filtered structure dominated by larger, sexually mature individuals, particularly females, supporting the interpretation of the river as a size-selective reproductive habitat. These patterns are consistent with the role of spawning migration as a size-selective biologicalfilter that transfers variability generated in marine feeding habitats into freshwater reproductive output.

Despite these constraints, this study contributes novel, system-level insight into how interannual variability in size structure propagates across the Black Sea-Danube continuum. By integrating marine and riverine components within a unified analytical framework, the results underscore the importance of considering habitat connectivity and size-selective migration when assessing anadromous fish populations.

Future research should combine size-based indicators with individual-based data, such as age, condition, reproductive status, and tagging or telemetry information, to better resolve the mechanisms driving cohort variability and migration timing. Integrating environmental covariates and fishing pressure into dynamic models would further strengthen understanding of how climatic and anthropogenic factors influence population structure and reproductive contribution in the Black Sea-Danube system.

Beyond its structural insights, this study highlights the potential management value of marine length–frequency information as an early indicator of spawning run composition in the Danube. If supported by future integration of standardized abundance indices (e.g., CPUE) and hydrological covariates, fluctuations in size structure at sea could contribute to anticipatory management of the riverine fishery by providing advance signals of spawning population structure. Such an approach would strengthen adaptive management within the Black Sea–Danube system by linking marine monitoring to riverine fishery regulation.

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