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RESEARCH ARTICLE

Hotspots and lost stocks: Critical analysis of *Atrina fragilis* (Pennant, 1777) population in the Sea of Marmara

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Abstract

Atrina fragilis, a large bivalve mollusc acting as an "ecosystem engineer" by providing hard substrate on the seabed, is under serious threat in the Mediterranean basin, particularly due to bottom trawl fisheries. This study was conducted in October 2023 to determine the distribution, population density, and morphometric characteristics of *A. fragilis* populations in the Sea of Marmara. Field surveys comprised bottom trawl operations carried out at nine stations within a depth range of 26.7 m to 115 m. It was determined that the population density of the species exhibited distinct variation among regions. The maximum individual density was recorded in the Ergene Basin (ST-8) with 3172 individuals/km², followed by Marmara Ereğlisi (ST-9) with 1034 individuals/km². Shell lengths of the examined individuals (N=65, 60 live, 5 dead) ranged between 10.2 cm and 30.3 cm. The findings revealed that *A. fragilis* forms viable populations in the mesophotic zone of the Sea of Marmara; however, its distribution is patchy and sparse in areas subject to intense fishing pressure. These results highlight the necessity of mapping sensitive habitats where the species is densely present and developing conservation strategies within fisheries management plans.

Keywords: *Atrina fragilis*, population density, bottom trawl, benthic ecology, Sea of Marmara

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Introduction

Large bivalve molluscs belonging to the family Pinnidae are commonly referred to in the literature and colloquially as "fan mussels" or "pen shells" due to their distinctive wedge-shaped morphology (Tyler-Walters and Wilding 2017). Members of this family are morphologically clearly distinguished from other bivalve groups by their triangular, thin, and fragile shell structures, which allow them to embed vertically into the sediment. The taxonomic distinction between the two extant genera of the family, *Pinna* Linnaeus 1758 and *Atrina* J. E. Gray 1842, is based on the continuity of the nacreous layer on the inner surface of the shell; in *Atrina* species, this layer exhibits a discontinuous structure (Tyler-Walters and Wilding 2022). Exhibiting a widespread but patchy biogeographic distribution globally, these organisms generally exist as isolated metapopulations where gene flow is limited (Leal-Soto *et al*. 2011; Stirling *et al*. 2018). A distinct differentiation exists between the species in terms of habitat niches; while *P. nobilis* is predominantly associated with *Posidonia oceanica* (Linnaeus) Delile 1813 meadows in shallow coastal waters, *A. fragilis* (Pennant 1777) prefers deeper, soft, or detritic bottoms below the limit of photophilic algae, thus occupying an ecologically distinct zone (Poutiers 1987; Fryganiotis *et al.* 2013).

Atrina fragilis, as a well-known representative of this genus, is considered one of the largest bivalve species in European seas, with dimensions reaching up to 48 cm in shell length (Tyler-Walters and Wilding 2017). Although known to be distributed across the Atlantic Ocean and the Mediterranean, populations of this species are generally characterized by low individual density and patchy distribution (Chaillot 2022). Therefore, *A. fragilis* has been evaluated as a "rare species" in many regions, especially in areas where trawl pressure is intense (Solandt 2003; Fryganiotis *et al*. 2013). Records regarding the presence of the species have been documented from different sub-regions of the Mediterranean, including the Alboran Sea, Balearic Sea, open waters of the Adriatic Sea (Šimunović *et al*. 2001), Thermaikos Gulf of the Aegean Sea (Fryganiotis *et al*. 2013), and all coasts of Türkiye except the Black Sea (Demir 2003; Öztürk *et al*. 2024; Çınar *et al*. 2024, 2025). Regarding habitat preferences, *A. fragilis* occurs in detritic or muddy sand habitats within the circalittoral zone (Gamulin-Brida 1974; Šimunović *et al*. 2001). While the species exhibits a wide bathymetric distribution from surface waters down to approximately 600 m depth, it is mostly recorded in dense populations within the 25–50 m depth range, with live individuals encountered up to 256 m depth in the Adriatic (Šimunović *et al*. 2001). These ecological characteristics make *A. fragilis* remarkable not only from a biogeographical perspective but also as a species supporting benthic biodiversity (Çınar *et al*. 2025).

Atrina fragilis plays a critical role as an "ecosystem engineer" by providing hard substrates on soft sediment bottoms, thereby creating habitats for rich epifaunal communities and enhancing local biodiversity (Çınar *et al*. 2025). However, *A. fragilis* are under serious threat due to habitat destruction and anthropogenic pressures (Hall-Spencer *et al*. 1999). Although the species lacks commercial value for human consumption, it is systematically extracted as incidental bycatch. Seabed-skimming gear, specifically bottom trawls and dredges, mechanically disturbs the benthic habitat, triggering drastic population declines and driving local extirpations in heavily fished zones (Fryganiotis *et al*. 2013). In addition to strictly benthic gears, pelagic purse seines operating in shallow coastal waters frequently interact with the seabed, exerting unintended physical pressure on these fragile bivalves (Akçay *et al.* 2025). Moreover, although bottom trawling is strictly prohibited in the Sea of Marmara (Anonymous 2024), illegal coastal trawling and unregulated small-scale dredging networks continuously amplify the mechanical stress on local populations (Karabacak and Deval 2023). The physical impact exerted by trawl nets can lead to the fragmentation of individuals with fragile shell structures, their dislodgement, and even mass strandings on the shore (Šimunović *et al.* 2001; Chaillot 2022). Furthermore, uncertainties regarding the species larval dispersal dynamics (Stirling *et al.* 2018) and biological sensitivities such as slow growth and late sexual maturity limit the recovery capacity of damaged stocks (Tyler-Walters and Wilding 2017).

In the waters of the United Kingdom, due to severe population losses detected, *A. fragilis* has been included within the scope of the "Biodiversity Action Plan" (UK BAP) (Anonymous 1994) and placed under legal protection by the Wildlife and Countryside Act 1981 (Solandt 2003; Tyler-Walters and Wilding 2017). Conversely, in the Mediterranean Basin; habitat destruction, intensive coastal development, anoxic conditions linked to eutrophication, and particularly fishing activities that physically dredge the seabed continue to pose a destructive threat to local populations of the species (Šimunović *et al.* 2001; Solandt 2003). These anthropogenic pressures not only lead to the depletion of stocks but also cause the disruption of benthic habitat integrity. However, despite the risks it is exposed to, there is currently no binding legal protection status or international action plan for *A. fragilis* across Europe or on a Mediterranean scale (except the United Kingdom), similar to that established for *P. nobilis* (Fryganiotis *et al.* 2013).

Although studies conducted on *A. fragilis* in the Mediterranean Basin provide significant information regarding the species' distribution (Šimunović *et al.* 2001; Fryganiotis *et al.* 2013), quantitative data on the current status of the population in the Sea of Marmara remain quite limited. To address this gap, the present study aimed to reveal the distribution and population structure of the species in deep-water habitats that are inaccessible via SCUBA and free-diving methods. Based on the fundamental population data obtained, this research aims to highlight the presence of the species in these deep bathymetric zones. Consequently, a primary focal point is to strictly prevent the misidentification of *A. fragilis* individuals as the protected *Pinna nobilis* in future fishery surveys and incidental bycatch records. The presented results are expected to provide a scientific basis for understanding the deep benthic areas of the Sea of Marmara and for ensuring accurate species identification within conservation programs that incorporate fisheries stakeholders into the monitoring processes.

Materials and Methods

The Sea of Marmara constitutes a biological corridor connecting the Black Sea and the Aegean Sea (Mediterranean) (Öztürk and Öztürk 1996). Despite being subjected to cumulative anthropogenic pressures stemming from intensive industrial activities, maritime traffic, and coastal settlements in its vicinity, this inland sea system still harbours high biological diversity thanks to its unique two-layered current structure and oceanographic characteristics (Çınar *et al*. 2025).

Field surveys were carried out in October 2023 using the research vessel R/V YUNUS-S belonging to Istanbul University. Biological samplings were performed using the demersal bottom trawl method at a total of nine stations selected to represent the benthic habitat heterogeneity and different depth contours of the Sea of Marmara (Figure 1). In order to standardize the sampling effort and Catch Per Unit Effort (CPUE), the haul duration for each trawl operation was fixed as 15 minutes, and the towing speed was maintained at an average of 2.5 knots. Operations were conducted across a depth range varying between 26.7 m and 115 m; thus, the aim was to reveal the variation in species composition and population structure in different bathymetric zones along the depth gradient.

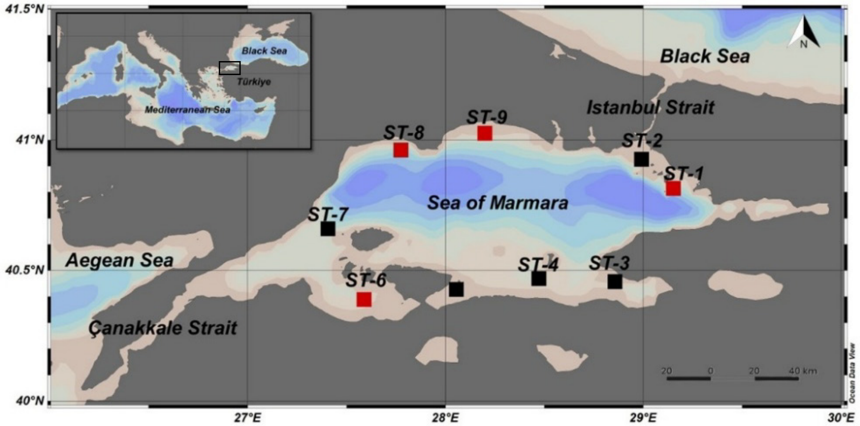

Figure 1. Sampling stations for the field survey carried out in the Sea of Marmara in October 2023 (Red squares indicate stations where live individuals of *Atrina fragilis* were recorded, while black squares represent stations where the species was not detected (absent) during the survey.)

The geographical coordinates, sampling dates, and depths of the sampled stations are presented in detail in Table 1. Although the field surveys were primarily designed to establish a general inventory of the demersal macrofauna biodiversity of the Sea of Marmara, the analyses conducted within the scope of this study focus on the evaluation of the distribution dynamics and population parameters (abundance, biomass, and morphometric characteristics) of individuals belonging to the family Pinnidae (specifically *A. fragilis*) extracted from the total catch composition.

To estimate the areal density, the methodology described by Sparre and Venema (1998), which is accepted as a standard approach in demersal stock assessment studies, was adopted. This method relies on calculating the effective area physically swept by the trawl net on the seabed and enables the conversion of Catch Per Unit Effort (CPUE) into areal density. The formula used is as follows:

$a = V \,.\, t \,.\, hr \,.\, X^2$

In this equation, "a" represents the swept area in square kilometres (km^2); "V" denotes the towing speed of the vessel in knots; "t" indicates the duration of the haul in hours; "hr" refers to the length of the head rope in meters; and "X^2" stands for the fraction of the head rope length, representing the effective horizontal opening of the net.

During the field surveys, the actual head rope length (hr) of the trawl net was measured as 25 m. As referenced in similar benthic studies conducted in the Sea of Marmara and the Mediterranean (Çınar *et al.* 2025), the fraction of head rope length (X^2) was accepted as 0.5 in this study as a conservative approach. Since the vessel speed was standardized at an average of 2.5 knots and the operation duration at 15 minutes (0.25 hours) during the field surveys, the swept area for each station was fixed at 0.015 km^2, and all density calculations were performed based on this value.

Live and dead *A. fragilis* individuals were sorted from the total catch composition obtained from trawl operations and transported to the laboratory. The sampled materials were subjected to biometric evaluation. Morphometric measurements were performed with millimetric precision using callipers, following the standard protocols for the family Pinnidae (Garcia-March and Nardo 2006). Within this context, the maximum axis length between the umbo and the posterior end was recorded as "Shell Length (L)"; the widest distance along the dorso-ventral axis as "Shell Width (W)"; and the vertical distance at the most inflated region of the shell as "Shell Thickness (T)". The population structure of the species was defined based on the obtained morphometric dataset (Width, Length, Thickness), and the relationships between these variables were evaluated statistically.

Prior to statistical analyses, the distribution characteristics of the morphometric variables (Length, Width, and Thickness) were assessed using the Shapiro-Wilk normality test. While 'Length' and 'Width' exhibited normal distribution, 'Thickness' showed a right-skewed distribution (Shapiro-Wilk $p<0.05$). Therefore, morphometric measurements were transformed using the natural logarithm (ln). The assumption of homogeneity of variances was verified using Levene's Test ($p > 0.05$). However, due to the highly unbalanced sample sizes (Live: 60; Dead: 5), Welch's t-test was employed for pairwise comparisons. Additionally, the non-parametric Mann-Whitney U test was conducted as a robustness check to confirm the findings, as suggested for small and unbalanced subgroups. Similarly, for the One-way Multivariate Analysis of Variance

(MANOVA), Pillai's Trace statistic was selected to evaluate the morphometric differentiation, as it is more robust to unbalanced designs compared to Wilks' Lambda. Principal Component Analysis (PCA) was also employed to visualize the multivariate relationship and examine potential clustering patterns between the groups. Finally, Pearson Correlation analysis was performed to determine the relationship between the log-transformed morphometric variables and the depth gradient. The statistical significance level was set at α= 0.05 for all analyses.

Table 1. Depth and coordinate information of the trawl sampling stations in the Sea of Marmara

Station	Date		Coordinates	Depth (m)
ST-1	15.10.2023	Start	40°50.913"N 29°08.160"E	57.7
		End	40°50.394"N 29°07.852"E	76.3
ST-2	16.10.2023	Start	40°55.732"N 29°00.230"E	28.1
		End	40°55.730"N 29°00.229"E	31.6
ST-3	17.10.2023	Start	40°26.494"N 28°53.896"E	94.5
		End	40°26.570"N 28°55.862"E	95.6
ST-4	18.10.2023	Start	40°26.508"N 28°29.807"E	45.8
		End	40°26.158"N 28°27.883"E	41.6
ST-5	19.10.2023	Start	40°26.546"N 28°03.026"E	37.8
		End	40°25.673"N 28°01.903"E	43.7
ST-6	21.10.2023	Start	40°21.775"N 27°34.725"E	26.7
		End	40°21.523"N 27°32.845"E	36.0
ST-7	21.10.2023	Start	40°36.728"N 27°23.047"E	109.0
		End	40°37.227"N 27°24.336"E	115.0
ST-8	24.10.2023	Start	40°58.184"N 27°44.476"E	46.0
		End	40°58.278"N 27°48.131"E	50.0
ST-9	24.10.2023	Start	41°02.634"N 28°07.326"E	27.0
		End	41°02.637"N 28°06.151"E	30.0

Results

The presence of *Atrina fragilis* (Figure 2) was detected in four of the total nine trawl operations conducted across the Sea of Marmara (Frequency of occurrence: 44%) (Figure 2). Based on the calculations using the swept area method, it was determined that population densities exhibited distinct variations among the stations (Table 2, Figure 2). The maximum individual density was recorded at station ST-8 (Ergene) with 3172 ind./km², followed by station ST-9 (Marmara Ereğlisi) with 1034 ind./km². Relatively lower density values were observed at stations ST-1 (Sedef Island) and ST-6 (Erdek), calculated at approximately 138 ind./km² for both stations.

Figure 2. *Atrina fragilis* specimen collected during the field sampling.

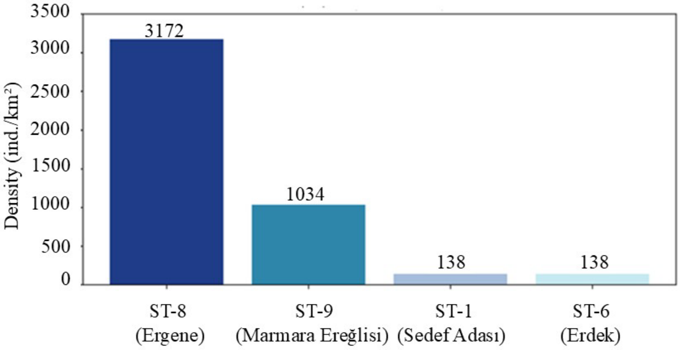

Figure 3. The population density of *Atrina fragilis* at stations in the Sea of Marmara

Table 2. Density of *Atrina fragilis* individuals at the sampling stations in the Sea of Marmara

Station	Area (km²)	Total Individuals	Live	Dead	Denstiy (individuals/km²)
ST-1	0.015	2	2	0	138
ST-2	0.015	0	0	0	0
ST-3	0.015	0	0	0	0
ST-4	0.015	0	0	0	0
ST-5	0.015	0	0	0	0
ST-6	0.015	2	1	1	138
ST-7	0.015	0	0	0	0
ST-8	0.015	46	44	2	3172
ST-9	0.015	15	13	2	1034
Total		65	60	5	

A total of 65 *A. fragilis* individuals (60 live and 5 dead) were sorted from the catch composition obtained during the field surveys, and morphometric measurements were performed. Marked differences were observed when examining abundance values among stations; the highest number of live individuals (N=45) was recorded at station ST-8 (Ergene), while the lowest (N=1) was recorded at station ST-1. When biometric characteristics were evaluated by station, it was determined that the largest individuals were present at station ST-1. Morphometric analysis of *A. fragilis* individuals revealed notable variations among the stations (Table 3). The largest individuals were recorded at ST-1, characterized by the highest mean values for shell length, width, and thickness. Conversely, individuals at ST-8, despite representing the highest population density, exhibited relatively lower mean morphometric values compared to ST-1. The shell dimensions recorded at ST-6 and ST-9 showed a high degree of similarity to each other, with both stations hosting generally smaller individuals than those observed at ST-1 and ST-8. Descriptive statistics regarding the numerical distribution and morphometric measurements of *A. fragilis* individuals obtained from all stations are summarized in Table 3, while the distribution ranges of the characteristics by station are visualized via boxplots in Figure 3.

Table 3. Descriptive statistics of morphometric measurements (mean±standard deviation, range) for *Atrina fragilis* individuals

Station	Length (cm)	Width (cm)	Thickness (cm)
ST-1	24.1±8.8 Min:17.8/Max:30.3	13.6±4.8 Min:10.2/Max:17.0	4.3±1.3 Min:3.4/Max:5.2
ST-6	15.6±6 Min:11.3/Max:19.8	11.4±2.6 Min:9.5/Max:13.2	3.0±0,3 Min:2.8/Max:3.2
ST-8	18.3±4.2 Min:10.2/Max:25.8	12.5±2.7 Min:5.1/Max:20.4	2.9±1.0 Min:1.4/Max:6.9
ST-9	15.2±3.7 Min:10.4/Max:20.6	11.0±2.9 Min:5.5/Max:15.8	2.9±0.6 Min:2.1/Max:3.9

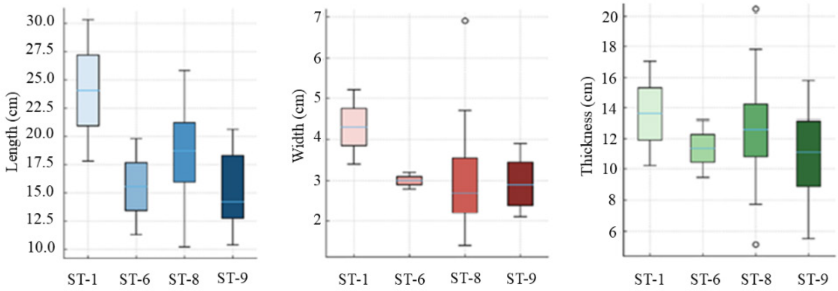

Figure 4. Boxplots illustrating the spatial variation of morphometric characteristics (Length, Width, and Thickness) of *Atrina fragilis* individuals across the sampled stations As detailed in the methodology, a logarithmic (ln) transformation was applied to all morphometric measurements (length, width, thickness) to achieve normal distribution and variance homogeneity, as the raw 'thickness' parameter exhibited a right-skewed distribution.

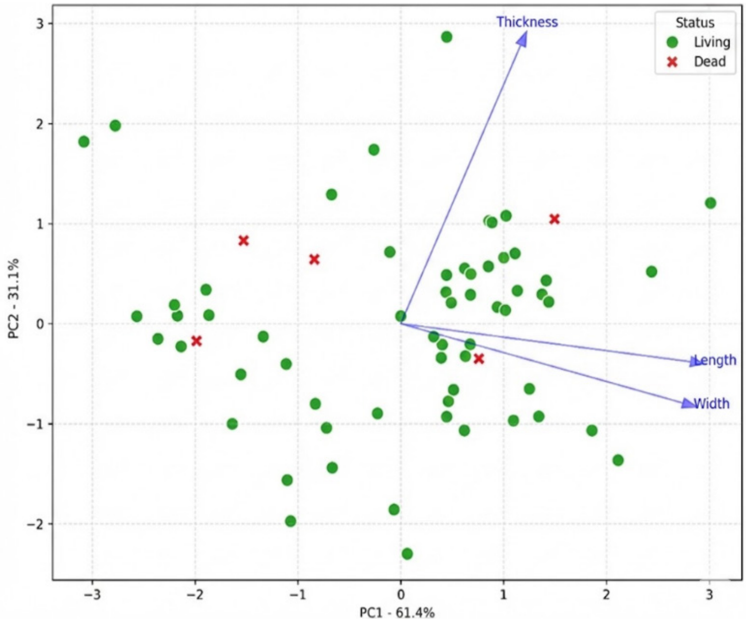

Figure 5. Principal Component Analysis (PCA) biplot visualizing the multivariate morphometric relationship between live (green dots) and dead (red crosses) *Atrina fragilis* individuals. The blue vectors indicate the contribution and direction of the morphometric variables (Length, Width, and Thickness) to the principal components. The first two axes explain 92.5% of the total variance (PC1: 61.4%; PC2: 31.1%).

Although the 'Width' and 'Length' parameters exhibited a normal distribution in their raw forms, a logarithmic transformation was applied to all morphometric measurements to ensure analytical consistency within the dataset and to enhance the homogeneity of variances. Consequently, comparative analyses (independent samples t-test) were conducted using these transformed data. Comparative analyses based on these transformed data revealed no statistically significant morphometric differences between live (n = 60) and dead (n = 5) individuals. Although the mean length (17.82 cm) and width (12.24 cm) of live individuals appeared numerically higher than those of dead individuals (15.90 cm and 11.20 cm, respectively), these differences were not statistically significant across pairwise comparisons (t-test and Mann-Whitney U test, $p > 0.05$). Furthermore, this lack of significant morphometric differentiation was consistently supported by multivariate approaches. One-way MANOVA indicated no significant variation between the groups regarding the linear combination of variables (Wilks' $\lambda = 0.961$, $F(3, 61) = 0.814$, $p = 0.491$). Finally, Principal Component Analysis (PCA), where the first two axes explained 92.5% of the total variance, revealed that dead individuals were homogeneously dispersed within the cluster of live individuals without forming any distinct spatial separation (Figure 4). Overall, mortality status did not exhibit a selective pattern regarding the morphometric characteristics of the sampled population.

To determine the variation in morphometric characteristics (Length, Width, Thickness) of sampled individuals along the depth gradient, a Pearson correlation analysis was performed using log-transformed (Ln) data and depth values (N=65). The results of the analysis are presented in Table 4.

Table 4. Correlation coefficients and their significance between morphometric parameters (Length, Width, Thickness) and depth

Parameter	Transformation	r (Correlation)	*p*-value	Result	n
Length	Natural Log (ln)	0.366	0.00271	Significant	65
Width	Natural Log (ln)	0.248	0.04646	Significant	65
Thickness	Natural Log (ln)	0.041	0.74448	Not Significant	65

The results indicate a positive and statistically highly significant correlation between length and depth ($r = 0.366$; $p < 0.01$). Similarly, a positive and statistically significant correlation was observed between width measurements and depth ($r = 0.248$; $p < 0.05$). Conversely, no statistically significant correlation was detected between the thickness parameter and depth ($p > 0.05$)

Discussion

A significant portion of historical data on *Atrina fragilis* originates from the Northeast Atlantic, particularly the waters of the United Kingdom. Records dating back to the mid-19th century documented that the species formerly formed dense and widely distributed populations in these regions (Jeffreys 1863; Solandt 2003). However, recent field observations have revealed that, largely as a consequence of anthropogenic pressures, the species now predominantly exists as isolated individuals or in extremely sparse assemblages (Solandt 2003). Regarding the Mediterranean Basin and specifically the Sea of Marmara, the first scientific record of *A. fragilis* was reported by Marion (1898), and it was subsequently included in the faunal checklist of the Marmara and Aegean Seas by Demir (2003). In recent ecological surveys, Çınar *et al*. (2024, 2025) reported the species to be relatively common on soft substrates south of the Marmara Islands, particularly within the 40–50 m depth zone. Nevertheless, these records essentially represent incidental findings from general benthic surveys. To date, no specific research aiming to determine the population structure and demographic characteristics (e.g., density, size distribution, growth parameters) across the species' entire distribution area in the Sea of Marmara has been conducted. This gap in the existing literature leads to uncertainties regarding the current status of natural stocks and highlights the lack of baseline reference data essential for the conservation and ecosystem-based management of the species.

In this context, the primary objective of the present study was to characterize the population status, distribution patterns, and morphometric characteristics (length, width, thickness) of *A. fragilis* in the Sea of Marmara. The findings aim to provide essential baseline data required for the development of regional conservation strategies and the establishment of sustainable management plans for this threatened species.

Bottom trawling has been identified as a chronic stressor for many benthic organisms, including long-lived and slow-growing sessile macroinvertebrates such as *A. fragilis*, due to the physical destruction it causes on the seafloor (Hall-Spencer *et al.* 1999; Pranovi *et al*. 2001; Šimunović *et al*. 2001; Solandt 2003; Fryganiotis *et al*. 2013). *Atrina fragilis* is highly susceptible to mechanical disturbances due to biological constraints such as its fragile shell structure, long life cycle, slow growth strategy, and re-burrowing incapacity (Hall-Spencer *et al.* 1999; Hiscock and Jones 2004). Indeed, Hall-Spencer *et al.* (1999) reported in a study conducted in the Gulf of Venice (Northern Adriatic) that trawling activities caused a population decline of over 70%, and approximately 90% of individuals caught as bycatch suffered lethal physical damage. Similarly, a comparative analysis in the Aegean Sea revealed that while the species formed healthy, dense, and sedentary populations in an area where trawling had been banned for over 25 years, its distribution was extremely sparse and irregular in the actively trawled zone (Fryganiotis *et al.* 2013).

Evaluating the data obtained from the present study in light of these previous studies, it is evident that illegal bottom trawling activities in the Sea of Marmara exert a similarly destructive impact on *A. fragilis* populations. The low individual density and fragmented distribution patterns observed in areas subjected to illegal trawling pressure corroborate that this anthropogenic factor constitutes a primary threat (Fryganiotis *et al.* 2013; Karabacak and Deval 2023). Therefore, since bottom trawling is already legally prohibited throughout the Sea of Marmara, strict enforcement of this ban and the implementation of enhanced surveillance mechanisms in identified sensitive areas are essential.

In the present study, *A. fragilis* individuals were recorded within a depth range of 26.7 m to 76.3 m. This bathymetric distribution corresponds to the circalittoral benthic zone. In terms of the overlying water column, these depths are characterized by mesophotic conditions, where reduced light penetration naturally limits photosynthetic activity. These findings are largely consistent with the general depth preferences of the species in the Mediterranean basin; indeed, Fryganiotis *et al.* (2013) reported that populations in the Aegean Sea are distributed in the 30–70 m range. Similarly, Poutiers (1987) and Šimunović *et al.* (2001) identified the 25–50 m depth range as the zone of highest density. These observed habitat preferences indicate that *A. fragilis* is structurally adapted to deep waters with mesophotic characteristics, where coastal hydrodynamic effects (e.g. wave energy) are reduced and sediment stability is optimized. This depth zone constitutes a suitable habitat for the species' long-lived and sedentary life strategy due to the environmental stability it offers.

In a recent study on the population density of *A. fragilis* in the Sea of Marmara, density values were reported in the range of 31–469 ind./km^2 (Çınar *et al.* 2025). However, the findings obtained in the present research reveal that the species can form much denser beds on a local scale within the Sea of Marmara. In particular, the densities of 3172 ind./km^2 recorded in the Ergene basin (ST-8) and 1034 ind./km^2 off Marmara Ereğlisi (ST-9) are significantly higher than previous regional records.

A comparison of these data with stocks across the Mediterranean Basin reveals that the *A. fragilis* population in the Sea of Marmara is considerably higher than that of the Aegean Sea (Fryganiotis *et al.* 2013), yet remains lower than historical Adriatic populations (Šimunović *et al.* 2001). Indeed, studies conducted in the Northern Adriatic have reported extremely high densities, with juveniles reaching 19284 ind./km^2 and adults 5489 ind./km^2 (Šimunović *et al.* 2001). However, it has also been reported that population density in the same region declined drastically from 250 ind./km^2 to 40 ind./km^2 due to the pressure of intensive scallop dredging (Hall-Spencer *et al.* 1999). On the other hand, research conducted in the Aegean Sea indicates that density values range between 0.03 and 6.27 ind./km^2 (Fryganiotis *et al.* 2013), remaining quite limited compared to the current findings in the Sea of Marmara. The situation differs in the Northeast Atlantic distribution; although very dense aggregations (2–4 ind./m^2) have been reported locally in UK waters (Canna Island) (Howson *et al.* 2012), the general population structure is emphasized to be extremely sparse and the distribution fragmented (Solandt 2003; Tyler-Walters and Wilding 2022). The present study suggests that the Sea of Marmara holds the potential to be a more favourable refuge or breeding ground for *A. fragilis* compared to the Aegean Sea but also signals a risk of stock depletion due to illegal overfishing pressure, similar to the Adriatic example.

Literature data regarding the maximum size attainable by *A. fragilis* have been updated over time. While Poutiers (1987) defined the maximum shell length for the species as 35 cm, more recent studies in the Aegean Sea have reported individuals measuring 42.9 cm (Papoutsi and Galinou-Mitsoudi 2010) and even 46.53 cm (Fryganiotis *et al.* 2013). In the present study conducted in the Sea of Marmara, however, the shell length of the largest individual was recorded as 30.3 cm, a value that remains below the maximum sizes recorded in the Mediterranean.

Research on the growth dynamics of this species highlights considerable variability in development rates. For instance, while Solandt (2003) estimated an average annual growth rate of 3–4 cm and a lifespan exceeding 12 years, Papoutsi and Galinou-Mitsoudi (2010) reported that individuals measuring 29.5–37.5 cm in shell length could range between 7 and 32 years of age, indicating that annual growth rates may decline to as low as 1.2 cm. By extrapolating these established Mediterranean growth rates to our morphometric data (shell length: 10.2–30.3 cm), the individuals in the present study are theoretically estimated to range from 4 to 16 years of age. This age-length inference suggests a mean annual growth rate of approximately 2.6 cm for the Sea of Marmara population. However, because direct age determination was not conducted, these values are strictly theoretical approximations. Furthermore, as Garcia-March and Marquez-Aliaga (2007) emphasize, age determination within the family Pinnidae is prone to systematic biases and inherent methodological challenges; therefore, such indirect age estimations must be interpreted with caution.

Examination of the demographic structure confirms the presence of juvenile individuals within the sampling area. Although limited in number, this indicates that active stock recruitment is ongoing and evidences the persistence of reproductive activities despite prevailing environmental pressures. Nevertheless, as a benthic invertebrate employing a broadcast spawning strategy, the reproductive success of *A. fragilis* is strictly contingent upon the spatial proximity of individuals (Solandt 2003). The predominantly low-density and patchy population structure currently observed in the Sea of Marmara significantly increases inter-individual distances. In marine broadcast spawners, such extreme spatial fragmentation drastically reduces gamete encounter rates and fertilization probability, a density-dependent reproductive failure widely documented as the Allee effect (Gascoigne and Lipcius 2004). Therefore, rather than being a theoretical risk, this limitation poses a concrete threat to the demographic recovery of the local population. In this context, the high-density aggregations (hotspots) identified in this study function as critical reproductive source populations. Preserving these localized dense patches is of strategic importance for maintaining the regional gene pool and ensuring the continuity of the species within the ecosystem.

The scarcity of scientific data regarding the reproductive biology of *A. fragilis* hinders the formulation of precise projections regarding the long-term viability of the Sea of Marmara populations. Literature suggests that reproductive cycles in similar temperate species are largely modulated by environmental factors such as water temperature and food availability (Angel-Perez *et al.* 2007; Freites *et al.* 2010). In its Mediterranean congener, *Pinna nobilis*, its population recruitment typically occurs during late summer and early autumn (Richardson *et al.* 1999; Cabanellas-Reboredo *et al.* 2009).

Mass mortality events in *P. nobilis* populations across the Mediterranean basin, driven by the pathogen *Haplosporidium pinnae* Catanese, Grau, Valencia, Garcia-March, Vázquez-Luis, Alvarez, Deudero, Darriba, Carballal, & Villalba, 2018, have brought large bivalve stocks to the brink of collapse. This ecological crisis has highlighted the significance of *A. fragilis*, which may offer a comparable contribution to maintaining benthic habitat complexity. As a species currently unaffected by this specific pathogenic threat, *A. fragilis* has the potential to function as an "ecosystem engineer" (Çınar *et al.* 2025), thereby supporting biodiversity within the Sea of Marmara's benthic ecosystem. Therefore, the conservation of *A. fragilis* populations is of strategic importance, not only for the preservation of the species itself but also as a proactive measure to help sustain benthic ecosystem functions that have been severely compromised by the decline of *P. nobilis*.

In conclusion, this study conducted in the Sea of Marmara reveals that while *A. fragilis* maintains viable populations in the region, it remains under severe pressure, particularly in areas subjected to illegal bottom trawling and mechanical benthic disturbances. Given the species' inherent biological constraints, namely slow growth, a sedentary lifestyle, and the necessity of aggregation for reproduction, the recovery of damaged stocks through passive conservation measures alone appears unlikely. In this context, the following management actions are recommended: (1) The strict enforcement of the existing basin-wide bottom trawling ban, accompanied by intensified surveillance mechanisms in high-density hotspots identified by this study, specifically ST-8 and ST-9; (2) The inclusion of the species in long-term monitoring programs under the 'Sensitive Indicator Species' status within the framework of the Sea of Marmara Conservation Action Plan; and (3) The investigation of genetic diversity and larval dispersal dynamics (connectivity) in future research. Implementing these steps is of vital importance for preserving the unique benthic biodiversity of the Sea of Marmara and ensuring its long-term ecological resilience.

Conclusions

This research presents a quantitative assessment of the density, demographic structure, and deep-water bathymetric distribution of *A. fragilis* populations in the

Sea of Marmara ecosystem. The findings demonstrate that the species exhibits a specific bathymetric range from 26.7 m to 76.3 m. Furthermore, the population structure is not homogeneous; rather, the species forms high-density aggregations in specific regions, particularly off the coasts of Ergene and Marmara Ereğlisi. These identified hotspots represent critical refuge areas for the persistence of the local population.

The fragmented distribution patterns observed highlight the species' severe vulnerability to mechanical benthic disturbances, including illegal coastal trawling. The conservation of this species, whose ecological significance in the Mediterranean Basin has critically escalated following the *Pinna nobilis* mass mortality crisis, is a strategic imperative. Consequently, it is essential to strictly enforce the existing basin-wide bottom trawling ban, specifically intensifying surveillance over the identified high-density hotspots. Furthermore, incorporating these baseline distribution data into future monitoring programs is crucial to definitively prevent the misidentification of *A. fragilis* as the legally protected *P. nobilis* in incidental bycatch records. Ultimately, the sustainability of *A. fragilis* populations in the Sea of Marmara relies on precise species identification and uncompromising habitat protection.

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S.Ç. The project was supervised and administered by S.Ç. All authors have read and agreed to the published version of the manuscript.

Sıcak noktalar ve kayıp stoklar: Marmara Denizi'ndeki *Atrina fragilis* (Pennant, 1777) popülasyonunun kritik analizi

Öz

Deniz tabanında sert substrat sağlayarak bir "ekosistem mühendisi" işlevi gören büyük bir çift kabuklu yumuşakça olan *Atrina fragilis*, Akdeniz havzasında özellikle dip trolü balıkçılığı nedeniyle ciddi tehdit altındadır. Bu çalışma, Marmara Denizi'ndeki *A. fragilis* popülasyonlarının dağılımını, popülasyon yoğunluğunu ve morfometrik özelliklerini belirlemek amacıyla Ekim 2023'te yürütülmüştür. Saha çalışmaları, 26,7 m ile 115 m derinlik aralığındaki 9 farklı istasyonda gerçekleştirilen dip trolü operasyonlarını kapsamaktadır. Türün popülasyon yoğunluğunun bölgeler arasında belirgin farklılıklar gösterdiği tespit edilmiştir. Maksimum birey yoğunluğu 3172 birey/km² ile Ergene Havzası'nda (ST-8) kaydedilmiş, bunu 1034 birey/km² ile Marmara Ereğlisi (ST-9) izlemiştir. İncelenen bireylerin (N=65, 60 canlı, 5 ölü) kabuk uzunluklarının 10,2 cm ile 30,3 cm arasında değiştiği belirlenmiştir. Bulgular, *A. fragilis*'in Marmara Denizi'nin mezofotik kuşağında yaşayabilir popülasyonlar oluşturduğunu, ancak yoğun balıkçılık baskısına maruz kalan bölgelerde dağılımının parçalı ve seyrek olduğunu ortaya koymaktadır. Bu sonuçlar, türün yoğun olarak bulunduğu hassas habitatların haritalandırılmasının ve balıkçılık yönetim planları dahilinde koruma stratejilerinin geliştirilmesinin gerekliliğini vurgulamaktadır.

Anahtar kelimeler: *Atrina fragilis*, popülasyon yoğunluğu, dip trolü, bentik ekoloji, Marmara Denizi

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