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The last hope: the struggle for survival of fan mussels in the Gulf of Erdek, Sea of Marmara, Turkey

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Abstract

This study presents the results of the first broad-scale assessment of the spatial distribution of the fan mussel (*Pinna nobilis* Linnaeus, 1758) population in the Gulf of Erdek (Sea of Marmara, Turkey), based on underwater surveys. The population density and structure of mussels were estimated by diving along strip transects between the shoreline and a depth of 15.8 m, in a study area of 9080 km^2. A total of 2164 mussels were counted, of which 78.8% were alive, and 21.2% were dead in 29 sites. The mean density was calculated as 18.3 ± 3.3 ind·100 m^{-2}, and recorded densities reached 71.2 ind·100 m^{-2} among the studied sites. Although mussel density was very high (>15 ind·100 m^{-2}) in nine sites, dead mussels were also recorded in the gulf. Benthic habitats, depth range, and exposure levels seem to play a crucial role in the spatial distribution and survival of fan mussels. The average height (± SE) was calculated as 19.5 ± 0.35 cm and 24.9 ± 0.37 cm for alive and dead mussels, respectively. The percentage of juveniles (≤20 cm) was 57% in the population, and they dominated in seagrass meadow beds and shallow waters. Despite many deaths due to uncertain causes, the results indicate a partially promising scenario for the fan mussel population in the Gulf of Erdek and highlight the existence of many alive juveniles that could play a primary role in the sustainability of the population. This situation is not static, as anthropogenic changes and human activities could affect population welfare in the future. These high-density sites need to be protected, and protection measures in these locations should include all effects that may cause incidental mortality.

Keywords: *Pinna nobilis*; critically endangered species; mass mortality; Mediterranean Sea; spatial distribution; population density; strip transects; conservation.

Introduction

The fan mussel (P*inna nobilis* Linnaeus, 1758), endemic to the Mediterranean Sea, lives even up to 45-50 years (Rouanet *et al*., 2015) and can reach to a size of up to 120 cm (Vicente & Moreteau, 1991). It is found along the northern and southern coasts of the Mediterranean from Spain to Turkey (including the Sea of Marmara) (Butler *et al*., 1993). It spreads in seagrass meadows, sandy bottoms, and rhodolith beds (Richardson *et al*., 1999; Katsanevakis, 2006; Kersting & García-March, 2017), occurring from the low tide level to approximately 60 m deep (Butler *et al*., 1993; Russo, 2012). Pinnids live partially buried in the substratum up to one-third of their length and attached to the substratum by their byssus filament (García-March *et al*., 2007a). *P. nobilis* feeds on both phyto and zooplankton; detritus accounts for the majority of the ingested element (Davenport *et al*., 2011). It can filter 5.99 liters of seawater per hour (Riva, 2002 in Vafidis *et al*., 2014). Thus, the species plays an essential ecological role, retaining large amounts of suspended particulate elements and improving water transparency (Basso *et al*., 2015). Their wide-surface shells also provide a suitable substratum for many species belonging to different taxonomic groups (Rabaoui *et al*., 2009).

The majority of fan mussel populations have been in sharp decline since the outbreak of a mass mortality event which started along the Spanish coasts in autumn 2016 (Vázquez-Luis *et al*., 2017). Mass mortalities (up to 100%) have been reported along the entire Mediterranean, including coasts such as Spain, France, Tunisia, Croatia, Italy, Cyprus, Greece and Turkey (Cabanellas-Reboredo *et al*., 2019; Kersting *et al*., 2019; Katsanevakis *et al*., 2021; Scarpa *et al*., 2021). High mortality rates have been observed among Pinnids (*Atrina pectinata* and *A. lischkeana*) due to virus-like parasites (Maeno *et al*., 2006, 2012). Histological and molecular evidence pointed out that a parasite *Haplosporidium pinnae* sp. nov. (Catanese *et al*., 2018) and bacterial pathogens such as *Mycobacterium* sp. (Carella *et al*., 2019) are likely responsible for the recent mass mortality of *P. nobilis*. Factors such as the destruction of its primary habitat (seagrass meadows), the deterioration of Mediterranean water quality (Vicente, 1990), several human activities such as illegal collection (Zavodnik *et al*., 1991), fishing (Katsanevakis, 2007), coastal infrastructure, and tourism activities (Öndes *et al*., 2020a) have damaged fan mussels in the past, and undoubtedly contributed to the decline of the species. Due to the sharp decline of its global population and its high risk of extinction, the species is strictly protected under several international and national laws and directives (e.g., the European Council Habitats Directive 92/43/EEC and SP/BD Protocol of the Barcelona Convention UNEP) as well as inside existing marine protected areas. The species has been assessed as "Critically Endangered" for the global and Mediterranean regional assessment since 2019 (Kersting *et al*., 2019).

Although mass mortalities were also reported in Turkey, reaching up to 100% in some locations (Öndes *et al*., 2020a; Öndes *et al*., 2020b; Özalp & Kersting, 2020; Acarlı *et al*., 2021), Öndes *et al*. (2020b) reported uninfected fan mussel population around Erdek (close to the south Marmara Islands), and Çınar *et al*. (2021a) reported high densities in the south of the Marmara Islands. However, just seven months after the latter study, Çınar *et al*. (2021b) reported the sad collapse of the population in the Marmara Islands. This study aims to characterize the ecology and density of the *P. nobilis* populations in the Gulf of Erdek (Marmara Sea, Turkey), one of the few populations unaffected by mass mortalities. The information provided in this study is essential, since the studied population may substantially contribute to securing the survival of the species in the Mediterranean Sea.

Materials and Methods

This study was conducted on the coasts of the Gulf of Erdek in the autumn of 2021. The Gulf of Erdek is a semi-enclosed wide embayment located in the southern part of the Sea of Marmara, Turkey (Fig. 1), and it is partially separated from the Sea of Marmara by the Kapıdağ Peninsula, Marmara, Paşalimanı, and Avşa Islands. The coast of the gulf is one of the least populated and industrialized regions around the Sea of Marmara. The region's population is about 32000, and about 10 times more with the effect of tourism in summer. It is affected by domestic factors (sewage and wastes) and human activities (tourism and small-scale fisheries) (Perçin-Paçal *et al*., 2019). The gulf is characterized by shallow and calm waters, and the insufficient current makes the area vulnerable to sudden changes (e.g., temperature, and pollution). The Gönen and Biga rivers are the transport routes carrying pollutants into the Gulf of Erdek (Keskin, 2007).

For surveying the fan mussel population, 29 sites were selected from different parts of the gulf (Fig. 1; Table 1). The selection of study sites was based on their exposure to different human activities, which were fisheries (1), anchoring (2), tourism (3), diving effects (4), and unexposed areas (5). Fishing activities based on gill nets and cast nets are carried out in the gulf. Illegal sea cucumber fishing by artisanal divers is known in the gulf. The tourism effect refers to the daily visitors who come to the beaches to swim. Diving activities refer to the sites where commercial diving is not permitted and SCUBA diving is performed for training purposes only. Data collection was performed by SCUBA diving along strip transects in each site (Katsanevakis, 2007; Theodorou *et al*., 2017). A chain strip segmented at five-meter intervals with yellow plastic key holders was stretched perpendicular to the shoreline using a diving compass (Hastie & Tibshirani, 1990). The surveyed area was limited to the depth at which the density of the fan mussel ended. Two divers swam along the transect, counting all mussels (both alive and dead) encountered within 2 m wide corridors on both sides of the strip (Fig. 2A, 2B). Thus, a total area of 20 m^2

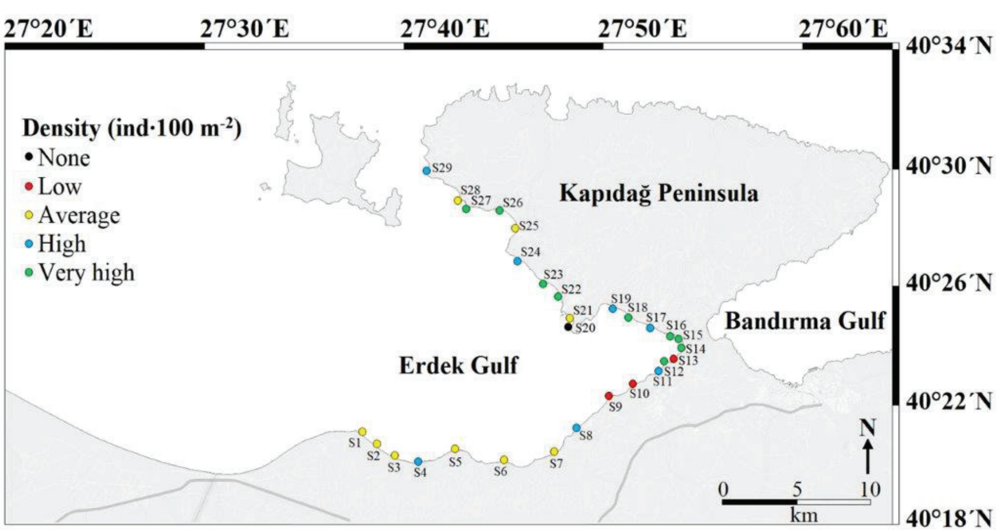

Fig. 1: Sampling sites and density status of *Pinna nobilis* in the Gulf of Erdek, Sea of Marmara, Turkey.

Table 1. Details of sampling sites, transects and *Pinna nobilis* densities (ind·100 m^{-2}) in the Gulf of Erdek.

Site		Transect				Density (ind·100 m^{-2})		
No[a]	Coordinate	Exposure type[b]	Distance (m)	Depth (m)	Surveyed area (m^2)	Alive	Dead	Status[c]
S1[Sa]	40.32500° N, 27.63722° E	F	110	14.1	440	9.1	3.0	A
S2[Sa]	40.31833° N, 27.64805° E	F	80	4.5	320	9.4	3.8	A
S3[Sa]	40.31138° N, 27.66138° E	F	140	14.6	560	5.9	2.5	A
S4[M]	40.30777° N, 27.67972° E	F	105	13.1	420	11.0	2.9	H
S5[R]	40.31500° N, 27.70777° E	F	50	12.0	200	6.0	3.5	A
S6[Sa]	40.30889° N, 27.74417° E	F	40	8.2	160	3.1	1.9	A
S7[M]	40.31389° N, 27.78306° E	F	120	14.6	480	8.3	4.0	A
S8[Sa]	40.32722° N, 27.79944° E	U	65	8.8	260	10.0	0.8	H
S9[Sa]	40.34583° N, 27.82361° E	U	95	14.6	380	4.5	1.3	L
S10[Sa]	40.35306° N, 27.84194° E	U	60	12.2	240	2.9	2.9	L
S11[Se]	40.36056° N, 27.86167° E	U	45	6.9	180	12.2	1.1	H
S12[Sa]	40.36583° N, 27.86472° E	U	70	8.3	280	30.7	1.4	VH
S13[G]	40.36639° N, 27.87222° E	U	45	6.9	180	2.8	1.1	L
S14[Se]	40.37472° N, 27.87972° E	U	75	6.3	300	64.0	12.0	VH
S15[Se]	40.38056° N, 27.87694° E	U	85	7.1	340	71.2	13.2	VH
S16[Se]	40.38278° N, 27.87056° E	T	90	11.1	360	32.5	4.2	VH
S17[Sa]	40.38694° N, 27.85500° E	T	70	14.1	280	12.1	3.2	H
S18[Sa]	40.39306° N, 27.83861° E	T	110	10.8	440	43.2	3.2	VH
S19[Sa]	40.39833° N, 27.82750° E	A	45	9.9	180	11.7	5.6	H
S20[Sa]	40.38750° N, 27.79444° E	D	95	12.4	380	0.0	14.2	N
S21[Sa]	40.39167° N, 27.79583° E	A	20	2.1	80	7.5	1.3	A
S22[Sa]	40.40500° N, 27.78667° E	T	95	13.5	380	31.3	5.8	VH
S23[Se]	40.41333° N, 27.77472° E	A	65	10.4	260	34.6	3.8	VH
S24[M]	40.42583° N, 27.75583° E	U	70	11.3	280	11.8	5.7	H
S25[Sa]	40.44417° N, 27.75500° E	T	105	11.8	420	7.9	6.2	A
S26[Se]	40.45556° N, 27.74111° E	T	80	9.2	320	33.4	17.8	VH
S27[Se]	40.45639° N, 27.71639° E	U	60	11.1	240	29.6	6.7	VH
S28[Sa]	40.46000° N, 27.71167° E	U	105	8.9	420	9.8	2.9	A
S29[Sa]	40.47639° N, 27.68806° E	A	75	8.4	300	13.3	4.7	H

[a] Dominant habitat: [G]: gravelly, [M]: muddy, [R]: rocky, [Sa]: sandy, [Se]: seagrass meadow

[b] D: diving, F: fisheries, A: anchoring, T: tourism effect, U: unexposed

[c] N: none, L: low, A: average, H, high, VH, very high

was surveyed between the two marked segments. Depth was measured with a digital dive computer at the mid-point per segment. Defining the habitat characteristics was classified according to the International Union for Conservation of Nature (IUCN, 2021): seagrass meadows (1), shellfish beds (2), rocky (3), sandy (4), muddy (5), and gravelly sediment (6). Alive and dead mussels could be easily distinguished. While alive mussels reacted to any effect (approaching close, touching, etc.), dead mussels were unresponsive, or open valves not closed and contained no tissue. Mussels in which the shell form was damaged (broken, plucked, cracked, etc.), were defined as damaged alive or damaged dead (Fig. 2C). Many dead fan mussels which were washed ashore were also found in the study areas (Fig. 2D). Unburied mussels were not considered because they may be transported haphazardly by the current, adversely affecting the distribution results. The mean density of each site was calculated as the number of individuals per hundred square meters (ind·100 m^{-2}). The part of the littoral zone exposed at low water

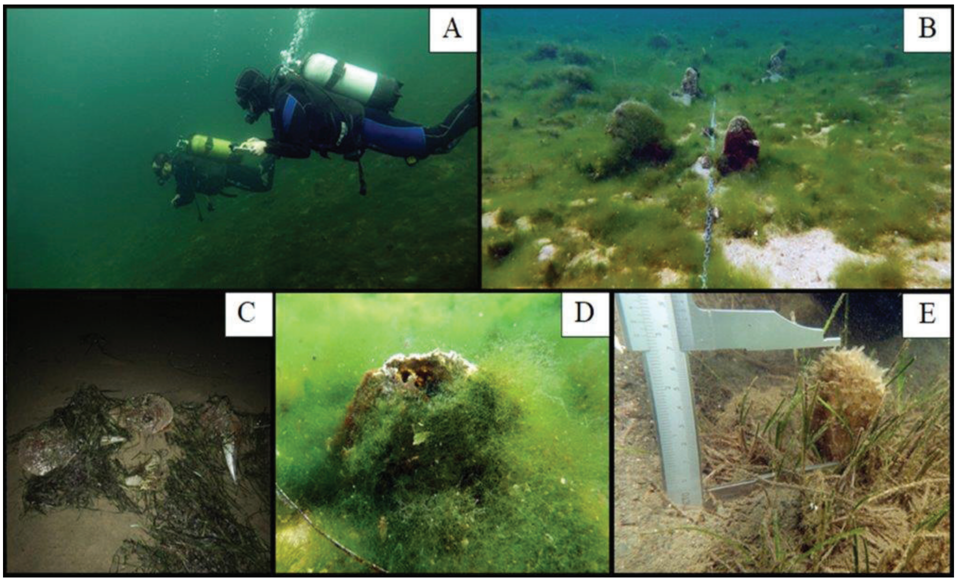

Fig. 2: Divers who swam along the transect (A), alive fan mussels observed along the strip transect (B), wracked dead shells on the coastline (C), buried and damaged specimen (D), and an alive juvenile with 7.7 cm unburied length (UL) in the Gulf of Erdek.

and submerged at high water is the foreshore (0-2 m). The foreshore provides some protection to the backshore against the full effects of the wave and tidal energy. The surf zone (2-14 m) is where waves break due to depth limitation. In total, a 9080 km^2 area was surveyed from the shoreline up to 15.8 m depth. A relative estimation scale was used to calculate density: low (<5 ind·100 m^{-2}), average (5-10 ind·100 m^{-2}), high (10-15 ind·100 m^{-2}) and very high (>15 ind·100 m^{-2}) (Rabaoui *et al*., 2008). The morphological features of fan mussels were measured *in situ* to avoid unnecessary removal and disturbances. The unburied length (UL), maximum width (W), and width at sediment level (w) were measured with a multi-caliper to the nearest millimeter (Fig. 2E). The total height of the fan mussel (H_t, in cm) was estimated using this equation:

$$H_t = UL + h$$

where h is the buried length which is equal to 1.79w + 0.5 (García-March *et al*., 2002). Specimens with a H_t up to 20 cm are considered juveniles, and those larger than 20 cm are considered adults (Šiletić & Peharda, 2003). The statistical treatment of the data was conducted with SPSS v0.26. All data are reported as mean values with standard error (mean ± SE). The normality of the data was checked using the Kolmogorov-Smirnov test. Significance levels for all statistical tests were established at p = 0.05 a prior (Sokal & Rohlf, 1969).

Results

A total of 2164 individuals of fan mussels were recorded in the surveyed area; 1705 (78.8%) were alive and 459 (21.2%) were dead. Alive individuals were found at 28 out of 29 sites, and the mean density ranged from 0 to 71.2 ind·100 m^{-2} among sites with a mean 18.3 ± 3.3 ind·100 m^{-2}. According to the relative density scale, very high densities were recorded in nine sites, and the center side of the gulf (Site 14 and Site 15) hosts fan mussel beds reaching more than 50 ind·100 m^{-2} (Table 1). Densities of fan mussels showed significant difference among studied sites for alive (Kruskal-Wallis, H = 69.874, df = 28, $p < 0.05$) and dead mussels (Kruskal-Wallis, H = 48.604, df = 28, $p < 0.05$).

The surveyed area was characterized by the dominance of sandy habitat, which occupied 44% of the cover, followed by seagrass meadow with 26%. The sandy habitat was the most common, with 54% in the foreshore zone (0-2 m). Patchy seagrass meadows *Zostera marina*, *Cymodocea nodosa*, and *Chaetomorpha* sp. were observed where the depth is shallower than 9.3 m, and the highest concentration was determined from 1 to 6 m (90%). *Posidonia oceanica* has only narrow distribution in the north part of the Gulf of Erdek. When one goes deeper than 10 m, the transition from seagrass meadow to sandy and muddy habitat is evident. The shellfish bed, which was distributed to depths between 4.8 and 12.6 m, was observed only in a few sites in 4% of the study area. The highest density for alive mussels was recorded in settled seagrass meadows, with 55.2 ind·100 m^{-2}. The mussel density was low (<5 ind·100 m^{-2}) in the rocky, gravelly and shellfish bed substrata (Fig. 3). Densities of alive (Kruskal-Wallis, H = 209.13, df = 5, $p < 0.05$) and dead mussels (Kruskal-Wallis, H = 60.15, df = 5, $p < 0.05$) differed significantly according to the habitat types.

Alive mussels were recorded at depths between 0.3 m and 13.4 m, and dead mussels at depths between 0.8 m and 14.6 m. The majority (89%) of alive mussels was counted from shoreline to 6 meters depth, while dead mussels were concentrated deeper (4-12 m). Alive mussels were placed at a very high density from 2 to 6 m depth range (Fig. 4). Densities of fan mussels significantly differed between depth ranges for alive (Kruskal-Wallis, H = 116.3, df = 7, $p < 0.05$) and dead mussels (Kruskal-Wallis, H = 101.4, df = 7, $p < 0.05$). Alive juveniles (≤20 cm) were concentrated in the shallow part (0-4 m). Adult individuals were in the majority in deeper waters from 4 to 16 m (Fig. 4). Depth seemed to have had a relevant role

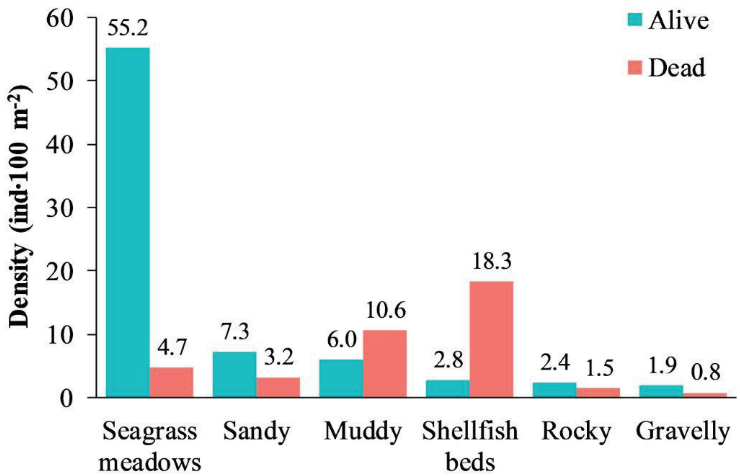

Fig. 3: *Pinna nobilis* densities (ind·100 m^{-2}) in different habitats.

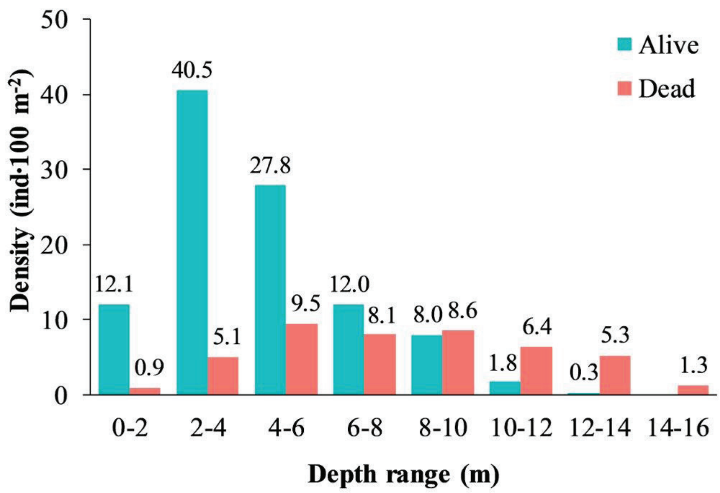

Fig. 4: *Pinna nobilis* densities (ind·100 m^{-2}) and mean size (H_t, cm) depending on the depth ranges.

in influencing population size structure (Kruskal-Wallis, H = 78.25, df = 6, p < 0.05), and significant differences in population size structure were found among the habitat types (Kruskal-Wallis, H = 19.40, df = 5, p < 0.05).

The average alive mussel density was recorded as 16.1 ind·100 m^{-2} for areas exposed to human activities and 23.9 ind·100 m^{-2} for unexposed areas. The mean mussel densities in the exposed (Mann-Whitney, U = 167.0, Z = -0.298, p = 0.766) and unexposed areas (Mann-Whitney, U = 161.0, Z = -0.507, p = 0.612) were not statistically different. The highest density (27.3 ind·100 m^{-2}) was recorded in sites where the tourism effect occurred. The density of alive mussels was quite low (8 ind·100 m^{-2}) in the fishery sites. All mussels were dead in Site 20, where the sportive diving training was conducted, and the highest dead mussel density (14.2 ind·100 m^{-2}) was determined there (Fig. 5). Significant differences occurred in the densities of alive (Kruskal-Wallis, H = 28.771, df = 4, p < 0.05) and dead mussels (Kruskal-Wallis, H = 10.960, df = 4, p < 0.05) between areas exposed to different human activities.

The rate of damaged fan mussel was calculated as 12.2% and 4.8% in the unexposed and exposed areas, respectively. The differences of damaged mussels between exposed and unexposed areas were not statistically significant (Mann-Whitney, U = 22812.5, Z = -0.203, p = 0.839). The rates of damaged fan mussels were 57.4%, 13.5%, 13.3%, 8.1% and 4.8% in diving, anchoring, fisheries, tourism affected and unexposed areas, respectively. Analyses showed no significant differences for densities of damaged mussels between sub-areas exposed to different human activities (Kruskal-Wallis, H = 2.557, df = 3, p = 0.634).

The average H_t and W of alive fan mussels were estimated as 19.5 ± 0.35 cm (11.8-31.4 cm) and 7.9 ± 0.15 cm (4.3-13.0 cm), respectively. Fifty-seven percent of the alive mussels (n = 118) were juvenile (≤20 cm) (Fig. 6). Significant differences occurred in the H_t (t = -10.163, n_1 = 207, n_2 = 132, p < 0.05) and W (t = -11.531, n_1 = 207, n_2 = 132, p < 0.05) between alive and dead mussels. The average H_t and W of dead fan mussels were estimated as 24.9 ± 0.37 cm (12.3-32.1 cm) and 10.5 ± 0.16 cm (4.8-12.7 cm), respectively. The dead mussels were mainly composed of adult specimens (87.9%), but juvenile individuals (12.1%) were also encountered. No significant differences occurred in the size of dead mussels among depths (ANOVA, F = 1.350, df = 7, p = 0.23) and habitat types (ANOVA, F = 1.159, df = 4, p = 0.33). Statistically, significant power relationships were determined between H_t and W, both alive (r^2 = 0.84, n = 207, p < 0.001) and dead mussels (r^2 = 0.80, n = 132, p < 0.001).

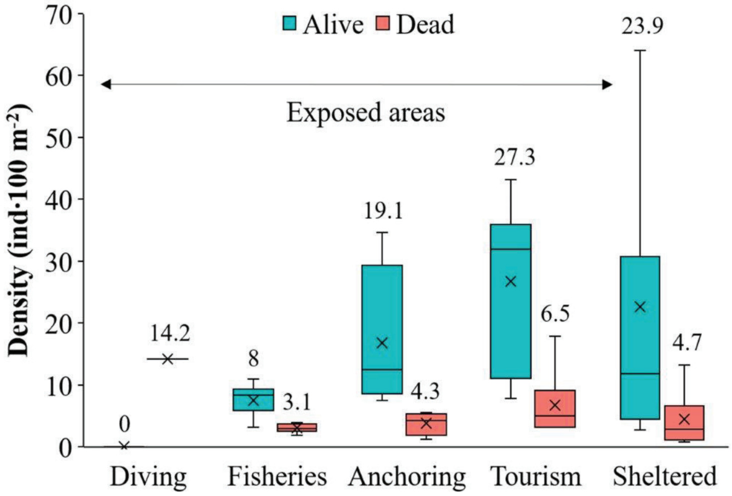

Fig. 5: Boxplot of the densities (ind·100 m^{-2}) for the *Pinna nobilis* in differently exposed and unexposed areas. Horizontal lines in the boxes represent the mean values, and whiskers represent the standard deviations. Error bars represent 95% confidence intervals.

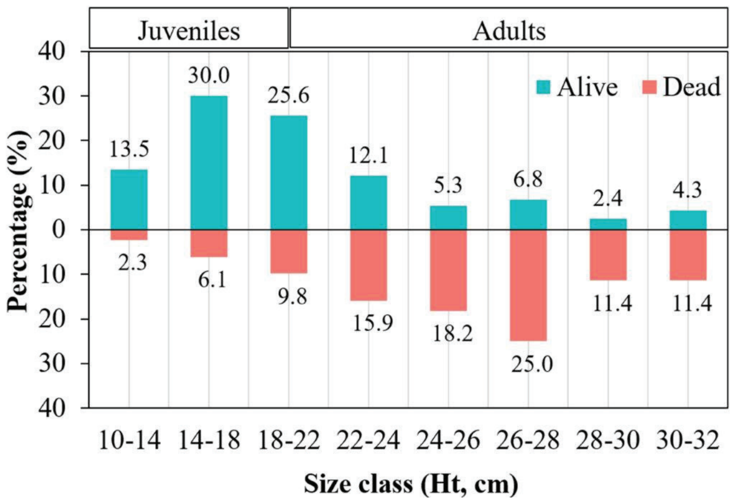

Fig. 6: Size frequency (H_t, cm) distribution of *Pinna nobilis* in the Gulf of Erdek.

Discussion

The current study highlighted the wide spread of the fan mussel beds throughout the Gulf of Erdek and the presence of fan mussel populations with high densities up to 71.2 ind·100 m^{-2}. Densities of fan mussels ranging from 0 to 130 ind·100 m^{-2} were reported in the Mediterranean Sea (Basso *et al*., 2015). Spatial distribution, abundance and mortality of fan mussels are affected by several factors such as environmental stress, including variations of temperature, salinity, depth, habitat (Hendriks *et al*., 2011; Vafidis *et al*., 2014; Kurihara *et al*., 2018) and human activities (Galinou-Mitsoudi *et al*., 2006; Deudero *et al*., 2015; Öndes *et al*., 2020a). Despite the collapse on the Turkish coasts of the Mediterranean, Aegean Sea and Dardanelles Strait (Öndes *et al*., 2020a; Öndes *et al*., 2020b; Özalp & Kersting, 2020; Acarlı *et al*., 2021; Çınar *et al*., 2021a; Künili *et al*., 2021), high-density alive fan mussel populations continue to exist in the Sea of Marmara. The mean density of *P. nobilis* was reported as 11 ind·100 m^{-2} by Öndes *et al*. (2020b) in the middle Aegean Sea, then a high mortality rate (97%) was reported in the same area (Öndes *et al*., 2020a). Much higher densities, up to 9 ind·m^{-2}, were reported in shallow waters (<5 m) from the Dardanelles Strait in 2014, but a devastating collapse was found in the same revisited region with high mortalities (99.68% and 85.71% in two different sites) in April 2020 (Özalp & Kersting, 2020). Çınar *et al*. (2021a) stated that the density of the fan mussel population ranged from 6 to 240 ind·100 m^{-2} in the southern part of the Marmara Islands in September 2020. In spring 2021, the same researchers (Çınar *et al*., 2021b) revealed a mass mortality event of fan mussel beds, which were reported to be healthy just seven months before.

All 54 fan mussels at Site 20 were dead, and this site was characterized by weak hydrodynamic factors and high turbidity. The densities of mussels differed between the surveyed sites (Table 1), and the spatial distribution was mainly related to habitat type. The highest densities (mean 55.2 ind·100 m^{-2}) were recorded in seagrass meadows, lower in the other habitats (Fig. 3). This result concurs with the widely known density relationship and habitat fidelity of fan mussels for *P. oceanica* seagrass meadows (Vázquez-Luis *et al*., 2014), rhodolith beds and boulders (Kersting & García-March, 2017) and other vegetated habitats (Katsanevakis & Thessalou-Legaki, 2009). Such habitat-related variations have a meaningful impact on *P. nobilis* survival and recruitment (Duarte *et* *al*., 1999; Katsanevakis & Thessalou-Legaki, 2009; Hendriks *et al*., 2011). Seagrass meadow offers to fan mussel the most suitable structures for the implantation of byssus filaments (García-March *et al*., 2007a), attenuates the water speed, and reduces the drag forces that act on the mussels increasing their optimal survival size (García-March & Kersting, 2006). Health status of seagrass meadow in the Gulf of Erdek is partially good, although some were striped, mashed or scraped, which are indicators of damage. It is thought that seagrass damage is caused by gill nets used by fishers and anchors used in boats.

The highest alive mussel densities mainly were restricted to the shallow zone between 2 and 6 m, progressively decreasing with depth (Fig. 4). Twenty-one percent of the alive mussels were recorded in the foreshore zone (0-2 m), most exposed to human effects. No alive mussels were found in the area outside the surf zone (2-14 m). There is also evidence of well-developed populations at sites deeper than 30 m (Kersting & García-March, 2017). In fact, due to hydrodynamics, densities might be higher at depth than in shallow areas. The main factor affecting the distribution of the species is not depth, and juveniles were concentrated in areas of seagrass that were usually in shallow waters. Therefore, we think that the depth distribution of mussels in the Gulf of Erdek is related to habitat preference. There is compelling evidence that depth significantly affects species density (Zavodnik, 1967; Šiletić & Peharda, 2003; Coppa *et al*., 2013). Tsatiris *et al*. (2018) argued that different densities are primarily due to the relationship of depth with several essential environmental parameters such as temperature, light intensity, hydrodynamics, bottom substratum, and primary and secondary productivity. Stagnant waters in protected areas where there is no human activity provide unexposed conditions for *P. nobilis*, and populations were determined to peak at less than a meter deep (Prado *et al*., 2014; Russo, 2017). Šarić *et al*. (2020) reported that shallow areas less exposed to sea current were at lower risk of pathogen transmission. In addition, seagrass meadows provide shelter for fan mussels against hydrodynamic movements, and density reaches its highest in shallow meadows where juveniles live (Hendriks *et al*., 2011). Kersting & García-March (2017) reported that natural recruitment might be affected by other factors such as predation, especially in protected sites where predators are abundant. The Gulf of Erdek is an unprotected area, and the excess of juveniles may be more associated with the absence of predators.

The Gulf of Erdek is a non-protected area under any management plan, and especially the surf zone of the gulf is exposed to different commercial and recreational human activities. The vast majority (57.4%) of the mussels were damaged in the population. Human effects are thought to contribute to this, but there is no conclusive evidence. A damaged *P. nobilis* may be more exposed to predators, thus increasing mortality from predation (García-March *et al*., 2007a). Many anthropogenic factors affect fan mussels, such as sewage discharges, coastal construction, habitat degradation, illegal extraction, fishing activities, and anchoring (Öndes *et al*., 2020a). The average mussel density in sites under pressure from fishing activities was relatively low (8 ind·100 m^{-2}). Artisanal fishery activities such as net-fishing may devastate the fan mussel beds (Vafidis *et al*., 2014; Vázquez-Luis *et al*., 2014). However, the fan mussel is highly vulnerable to direct anchor damage (Vázquez-Luis *et al*., 2015). Although fan mussel densities between exposed and unexposed areas were statistically insignificant (Fig. 5), there is substantial evidence that conservation strategies support the increase of mussel density (Vázquez-Luis *et al*., 2014; Deudero *et al*., 2015; Vázquez-Luis *et al*., 2017).

The majority of the population in the Gulf of Erdek is characterized by the predominance of small-sized (juvenile) individuals (Fig. 6), which were found in almost all sites, indicating successful recruitment in specific areas. Fan mussels grow fast in the first years of life, sizes show extreme variation among different stocks or even among groups of individuals inhabiting multiple depths at a similar habitat (Katsanevakis, 2006; García-March *et al*., 2007b; Kersting & García-March, 2017). *P. nobilis* population in the Gulf of Erdek is composed of smaller individuals (H_t ranged from 11.8 to 31.4 cm) when contrasted to the other Mediterranean populations (Katsanevakis, 2006; Centroducati *et al*., 2007; García-March *et al*., 2007b; Theodorou *et al*., 2017; Ruitton & Lefebvre, 2021). Size ranges of the fan mussel population from Dardanelles Strait are consistent with our results. H_t range was reported between 10.8 and 30.0 cm by Acarlı *et al*. (2021) and between 11.0 and 47.5 cm by Künili *et al*. (2021). Çınar *et al*. (2021b) reported that some juvenile individuals were observed in the south Marmara Islands. The average size of dead mussels was determined as 24.9 cm and it seems that many dead individuals are in that juvenile-adult limit (20 cm). Larger individuals were absent, mainly due to the young population in the Gulf of Erdek. The growth performance of populations in Erdek Gulf is unknown. Therefore, detailed population studies are needed to make a definite judgment about the population structure. Juveniles have a better reaction to pathogens (Šarić *et al*., 2020) and accordingly, their survival rate is quite high (Acarlı *et al.*, 2011). Although the main cause of such higher survival in juveniles than adults is unclear, the fact that juveniles with a high percentage have been observed in the study area indicates successful recruitment. The mean mortality rate of fan mussels was found as 21.2% (ranged between 4.4% and 100% at 29 sites) in the Gulf of Erdek. Similarly, Çınar *et al*. (2021b) reported that fan mussels were found at seven stations out of 10, of which 88% were dead in the south Marmara Islands (in the most recent study conducted in the region), and the highest number of dead individuals was encountered in shallow waters (0-4 m depth).

The percentage of population size reduction over the last ten years is ≥80%, and the pathogen that has caused the mass mortality event is still present in the Mediterranean, with continuing declines expected (Kersting *et al*., 2019). Mass mortalities of the *P. nobilis* populations reaching up to 100% occurred along the Mediterranean (Cabanellas-Reboredo *et al*., 2019), Adriatic Sea (Čižmek *et al*., 2020), Aegean Sea (Catanese *et al*., 2018;

Katsanevakis, 2019), Dardanelles Strait (Öndes *et al*., 2020b; Özalp & Kersting, 2020; Acarlı *et al*., 2021), Bosnia and Herzegovina (Čelebičić *et al*., 2020), and even the Sea of Marmara (Öndes *et al*., 2020b; Çınar *et al*., 2021a; Çınar *et al*., 2021b). The findings indicated that mass deaths were commonly caused by *H. pinnae* (Darriba, 2017; Vázquez-Luis *et al*., 2017; Catanese *et al*., 2018; Čižmek *et al*., 2020). According to recent research, deaths also seem to occur due to co-infection of the protozoa with bacteria such as *Mycobacterium* sp. or *Vibrio* sp. (Carella *et al*., 2019; Künili *et al*., 2021). There is no definitive report about the presence of pathogens in the Sea of Marmara yet. There is evidence of disease-related mass mortality of fan mussels in the Dardanelles Strait, connected to the Sea of Marmara (Öndes *et al*., 2020b; Özalp & Kersting, 2020; Acarlı *et al*., 2021). Künili *et al*. (2021) suggest that the spread of pathogens may occur earlier than expected in the Marmara Sea and the Black Sea. In April of 2021, there was a massive explosion of marine mucilage in the Sea of Marmara, so that many invertebrates of marine communities suffered mass mortality (Özalp, 2021; Topçu & Öztürk, 2021; Karadurmuş & Sarı, 2022). Çınar *et al*. (2021b) put forward that the cause of death might be associated with this catastrophic mucilage event. The effect of marine mucilage on fan mussel beds is not yet known. The Sea of Marmara also faces many enormous rivers and municipal sewage pollution, agricultural, and shipping activities. The survival of fan mussel beds, as opposed to anthropogenic pressures, human impacts, and potential pathogens, will largely depend on the relationship between rate of mortality and recruitment in the Gulf of Erdek.

Conclusions

The aim of this study was to give a better understanding of the distribution and densities of fan mussels in the Gulf of Erdek through new findings. Artisanal divers confirm the fan mussels have been in the study area since the beginning of the 2000s. No recent death has been seen yet, and fresh tissue has not been found in dead individuals, and living individuals are quite dense in the Gulf of Erdek. Whereas it is difficult to predict the extent of the mortality of fan mussels due to a lack of previous status of populations, the current available evidence shows high densities in the Gulf of Erdek. The presence of a high density of alive individuals in the study area is promising for the survival of the species. These areas are critical for recruitment and juvenile survival of fan mussels. The fan mussel was first protected in 1997 (In the Official Gazette of the Republic of Turkey dated 9 March 1997 and numbered 22928) and is still on the protected (prohibited) species list in Turkey. As recommended by the IUCN (Kersting *et al*., 2019), high-density sites in the Gulf of Erdek need to be protected, and protection measures should include all effects that may cause incidental mortality. Small-scale fisheries in the Gulf of Erdek must be regulated to minimize their direct impact on fan mussel beds. Using stable vessel buoys should be supported to reduce the effects of anchoring on seagrass meadows. It is also essential to carry out regular awareness campaigns to not harm the mussels for the visitors who come to the beaches for swimming. Öndes *et al*. (2020b) and Çınar *et al*. (2021a) had also suggested it for the south Marmara Islands previously. It is clear that these measures will contribute to the survival of fan mussel populations, and this contribution has been proven before in Marine Protected Areas (Rouanet *et al*., 2015; Vázquez-Luis *et al*., 2017). Although seagrass meadows are the primary habitat of the fan mussel, they have been severely damaged in the Mediterranean Sea (Marbá *et al*., 2014), so a special conservation plan is needed for the protection of seagrass meadows in the Gulf of Erdek. The populations' recovery may be possible by spreading larvae from unaffected sites and potential recolonization through exporting larvae (García-March *et al*., 2020; Kersting *et al*., 2020). Populations in affected areas may recover if at least some of the resident individuals in the Sea of Marmara as a *P. nobilis* reservoir show resistance to the disease. The geographical range of available data covers the entire Gulf of Erdek, but is not fully representative of the species bathymetric distribution of the population. Thus, the status of *P. nobilis* populations in the deeper part of their depth range needs further investigation. Further population studies are needed, including age-based growth performance and mortality rates of mussel populations in the Gulf of Erdek. Most importantly, the entire Sea of Marmara, including the Gulf of Erdek, should be regularly monitored to detect the presence/absence of pathogens that cause mass death in fan mussels.

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