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# Biological aspects, population and fishery dynamics of the non-indigenous pearl oyster *Pinctada imbricata radiata* (Leach, 1814) in the Eastern Mediterranean

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A B S T R A C T

The pearl oyster *Pinctada imbricata radiata* (Leach, 1814) is considered as an invasive species and despite its presence, for more than half of a century in the Mediterranean its fisheries in Greek waters is illegal, unregulated and unreported (IUU) due to lack of legal framework and fisheries exploitation. The present study is based on a three-level approach including a(n): (a) *in-situ* field sampling of live shell specimens, (b) estimation of biological and population parameters and (c) estimate of population stock state complemented with in-depth interviews conducted to fishers. The specimens of the pearl oyster were collected from two enclosed gulfs in Greek waters from November 2018 to October 2019. Asymptotic lengths ($L_\infty$) were estimated at 100.63 mm and 103.04 mm, in the North Evoikos and Saronikos Gulfs, respectively and the growth coefficient (K) was estimated at 0.47 year$^{-1}$ and 0.34 year$^{-1}$, respectively. The longevity of the species was estimated at 5 years. Total mortality coefficients (Z) were 1.92 year$^{-1}$ and 1.44 year$^{-1}$, in the two areas, respectively and the exploitation levels (E) were computed as 0.68 year$^{-1}$ and 0.65 year$^{-1}$, respectively. The results of the present study will fill the gaps in knowledge of pearl oyster to set up a reference base for its exploitation as a fishery resource based on invasive species.

## 1. Introduction

To date, the Mediterranean marine fauna has been gradually reshaped by the introduction and spread of invasive species (Galil et al., 2019; Zenetos and Galanidi, 2020). Although invasive species severely impact on the ecosystem biodiversity, structure and function (Sabelli and Taviani, 2014), certain of them provide benefits by: (a) replacing lost ecological functions, (b) adding redundancy that strengthens ecosystem resilience, and (c) becoming targets for local fisheries and aiming to balance economic returns (Chaffin et al., 2016). Gaps in knowledge about biology and population status pose a challenge for concerted actions to control invasive species transmission and dominance.

The Pteriidae family has a worldwide distribution, valid comparisons with other pearl oyster throughout the world (i.e., *Pinctada imbricate*, Roding, 1798, *Pinctada margaritifera* (Linnaeus, 1758), *Pinctada maxima* (Jameson, 1901), *Pinctada mazatlanica* (Hanley, 1856), *Pteria penguien* (Röding, 1798) and *Pteria sterna* (Gould, 1851)) will be established with the present data. Recent studies also reported two distinct species, *P. radiata* (Leach, 1814) and *P. fucata* (Gould, 1850) in the Mediterranean basis (Scuderi et al., 2019). The pearl oyster (*Pinctada imbricata radiata* (Leach, 1814)) is a benthic species inhabiting on sandbanks and coral rock (Strack, 2008). The species originates from the Indo-Pacific region and has been recorded in the Mediterranean as a non-endemic species since the 19th century (in 1874), soon after the opening of the Suez Canal (Zenetos et al., 2005). Since then, this species has spread-out and established in Eastern Mediterranean areas with a significant presence in Sicily, Malta and the nearby islands, Ionian and Adriatic (for review see: Theodorou et al., 2019). In Greece, the pearl oyster was intentionally introduced for mariculture during the mid-1950s (Serbetis, 1963) and since then, although it has low commercial interest, it is exploited as domestic commercial bivalve stock (Katsanevakis et al., 2008; Theodorou et al., 2011). The fishing activity of the species is carried out by scuba diving/dredging (the most common ways to catch the pearl oyster) despite that are forbidden.

The paradox of current national fisheries legislation is that the species is not included in the list of Presidential Decrees 86/98, 227/2003 and 109/2002 that regulate shellfish harvesting and therefore is considered illegal (Katsanevakis et al., 2011). The problem is aggravated by the discrepancy in the officially-reported bivalve catches. The Hellenic Statistical Authority (ELSTAT) recorded bivalve catches disaggregated in four species

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(i.e., Warty venus *Venus verrucosa* Linnaeus, 1758, Mediterranean mussel *Mytilus galloprovincialis* Lamarck, 1819, European flat oyster *Ostrea edulis* Linnaeus, 1758, and king scallop *Pecten maximus* (Linnaeus, 1758)) since 1982 (HELSTAT) (HELSTAT, 1984-2019). Intentionally and unintentionally misidentification of pearl oyster catches reported by the statistical authorities might attribute to the absence of this species from the list of commercially exploited bivalve species likely due to aggregated catches with of the above-mentioned bivalves and/or reported in the aggregated category of "other shellfish". Nevertheless, pearl oyster has been served as a dish in fish restaurants often as substitute for endemic oysters (i.e., *O. edulis*) which are increasingly rare if not already 'extinct'.

Knowledge of the population structure and dynamics of the species is useful to scientists, producers, and fishers involved in the collection and fishery of the non-indigenous-edible pearl oyster. The pearl oyster has established populations in Central (Italian waters: Stasolla et al., 2014; South of Sicily: Lodola et al., 2013) and Eastern (Barbieri et al., 2016; Theodorou et al., 2019) Mediterranean Sea and its morphometric parameters have been well-described (i.e., Tunisie: Tlig-Zouari et al. (2010); Maltese Islands: Deidun et al. (2014); Morocco: Amane et al. (2019)). In contrast, population dynamics for this species are limited to growth rate estimates calculated for the Eastern Mediterranean, Red Sea (Mohammed and Yassien, 2003) and in the Thermaikos Gulf (Manousis and Galinou-Mitsoudi, 2013). Hence. the aim of the present study is the estimation of morphometric relations and the comparison with the results from similar studies in other Mediterranean areas (i.e., Morocco: Amane et al. (2019), South of Sicily: Lodola et al. (2013), Tunisie: Tlig-Zouari et al. (2010)) and the first, to our knowledge, description of the fishery of the species in two areas and the estimation of life-history traits, mortality and population status in the Eastern Mediterranean. Considering also that

In the absence of official and field data on bivalve species catches, unconventional data sources, such as fishers' ecological knowledge is increasingly being used in data-poor areas such as the Eastern Mediterranean case, to narrow the gap of the available data (Theodorou et al., 2020). Despite its potential biases (Thurstan et al., 2016), fishers' ecological knowledge can be complementarily used with empirical data. This mixture of methodologies would aim to mitigate the problem of illegal, unregulated and unreported "IUU" fisheries of a non-endemic species by determining the minimum thresholds for management and subsequently narrow the "legislative gap".

## 2. Materials and methods

### 2.1. Study areas

The North Evoikos Gulf is an enclosed and relatively deep (max depth 425 m) coastal area located between the Greek mainland and the island of Evvoia. The area has limited communication with the Aegean Sea waters primarily at its northern part through the straits of Oraioi and secondarily through the narrow Evripus channel, at its southern part (Fig. 1). According to the limited published information concerning the hydrology and trophic status of the gulf, the North Evoikos is considered as a mesotrophic coastal basin with higher concentrations of nutrients and chlorophyll a (Chl a, annual mean 0.76 mg $m^{-3}$, range 0.25–4.87 mg $m^{-3}$) than the open Aegean Sea waters and comparable to similar coastal areas in Greece (Friligos, 1985; Metaxatos and Ignatiades, 2002). The North Evoikos Gulf has slightly colder and less saline waters than adjacent areas with values ranging through the year from 11.1 to 29.6 °C and 36.8–38.2 psu (Metaxatos and Ignatiades, 2002).

The Saronikos Gulf is an open coastal area with many small and bigger islands, communicating with the open waters of the Aegean Sea at its southern part. According to Pavlidou et al. (2019), the gulf is divided into four sub-areas: The outer and inner parts, the western part and the innermost Elefsis bay is separated from the other parts by the Salamis Island and forms an enclosed and shallow (30 m) bay (Fig. 1). The Elefsis bay is the most impacted part of the gulf due to industrial and shipping activities and is characterized as eutrophic in terms of nutrient concentrations (Pavlidou, 2012) whereas in terms of Chl a concentrations, its trophic status ranges from mesotrophic (annual average: $0.39 \pm 0.31$ mg $m^{-3}$, range 0.09–1.21) Strogyloudi et al., 2012 to eutrophic (range 1.16–1.84 mg $m^{-3}$) (Ignatiades, 2005). The annual temperature and salinity range in the inner part of the Saronikos Gulf, is 10 to 27.5 °C and 38.4 to 39.3 psu, respectively (Evangeliou and Florou, 2013).

### 2.2. Targeted interviews

Targeted interviews were conducted during winter–spring 2019 with professional fishers working in the pearl-oyster fishery. The methodological approach was based on expert opinion knowledge elicitation rather than on the statistical sampling, in cases where the classical survey does not give reliable results due to high complexity and lack of real credible data. Interviews were carried out privately (one-to-one sessions) to prevent influences by others, especially by the fisher's colleagues and in Greek by one person to ensure that questions were presented identically to minimize sampling bias. Interviews took place in the mooring/landing sites of the professionals.

Questionnaires were designed to be compatible with those used in socio-economic surveys conducted in other Greek coastal fisheries (Tzanatos et al., 2006) to facilitate comparisons. Questions were disaggregated in three main categories: (a) fishing effort estimation (i.e., seasonality of the fishery and number of active fishing days per season, and number and frequency of fishing gears used) and typology of fishing operations (i.e., number and quantities of the targeted species, types and frequency of fishing gears used, and peaks and minimum of catches), (b) problems faced during fishing operations, marketing aspects related to economic returns and market pathways and generic views on Common Fisheries Policy issues and fisheries legislation, and (c) demographic features (i.e., sex, age, educational level, marital status, place of origin and year of birth).

Descriptive statistics were applied, providing percentage contribution, mean and standard deviation (SD) values of several resulting responses. Comparisons of quantitative variables (i.e., number of active fishing days) were performed using one-way ANOVA parametric test between the number of fishing days as a dependent variable and month as an independent variable. Whenever a significant difference was detected ($p < 0.05$), a Tukey post-hoc pairwise comparison test was used to detect the responsible factors (Zar, 2010). The non-parametric chi-square test ($\chi^2$-test) was also used to examine whether there is a possible association between variables described with ratios.

### 2.3. In-situ sampling

*P. imbricata radiata* is characterized by bigger shell (height of the valve up to 75 mm) in full grown specimens than the latter (up 45 mm), is rounded in outline almost entirely red-brownish with darker radial strips, sculpture of dense and pointed process, organized in numerous rows, soft parts mainly orange (Scuderi et al., 2019). These features have been taking into account during the collection of the specimens for the distinction with the *P. fucata* species. Alive specimens of *P. imbricata radiata* were

**Fig. 1.** Sampling stations indicating the two studied areas (EV, North Evoikos and SAR, Saronikos gulfs).

randomly collected in four sampling trials from two enclosed gulfs, Saronikos and North Evoikos (Fig. 1) during an annual cycle (November 2018, February 2019, April 2019 and October 2019). Samplings were performed by SCUBA diving from mixed hard and soft substrates where specimens could be found in small patches at depths between 1 to 4 m. Care was taken to collect individuals from all size ranges. Thereafter, the specimens were cleaned from epizoic organisms and were preserved in the refrigerator. After removal of the soft parts, certain morphometric characteristics of the left valves and the shell were measured using a digital caliper to the nearest 0.1 mm.

For each specimen the following measurements were taken in the largest (left) valve (Fig. 2): (a) on the external side of the shell: height of the largest valve (SH); shell length (SL); hinge length (HL); shell width (SW), (b) on the internal side of the shell: the length and the width of the necreaous part of the shell (Ln1; Wn1, Ln2, and Wn2; with 1 and 2 indicating the largest (left) and smallest right valve, L and W, are the length and width, respectively), (c) the total wet weight (TW), the wet weight of the bony (FW) and the wet weight of the shell (SE). The condition factor (CF) was estimated from the equation CF = FW/TW∗100.

### 2.4. Morphometric relationships

The following relations were established, using linear regression analysis of log-transformed SH, as an independent variable, with the log-transformed dependent variables (Y) SL, HL, SW, L-Ln1, W-Ln1, L-Ln2, W-Ln2, TW, FW and SE. Descriptive statistics were applied, providing percentage contribution, mean and standard deviation (SD) values of several resulting parameters.

To minimize any variation resulting from allometric growth, all measurements were standardized according to Reist (1985): $X'_{i,j} = LnX_i - b.\left(LnSH_j - \overline{LnSH_i}\right)$ where $X'_{\mathrm{i,j}}$ is the standardized measurement of the i morphometric character; $LnX_i$ is the natural logarithm of i morphometric character measurement; $SH_j$ is the shell height of the individual j; $\overline{LnSH}$ is the natural logarithm of the mean shell height of pooled individuals and $b$ is the slope of the $LnX$ against $LnSH$ plot. The b value of each character was tested by Student's t-test (Zar, 2010) to verify if it was significantly different from isometric growth ($b = 3$, $p < 0.05$ for weights) (Froese et al., 2011) and ($b = 1$, $p < 0.05$ for other linear dimensions).

Principal component analysis (PCA) was used to test for the contribution of the above-mentioned characters to the configuration of shell shape variance. PCA is a linear dimensionality reduction technique that replaces the original variables with a smaller number of uncorrelated variables (Factors: F) while maintaining maximum variance and projecting the variables into a lower-dimensionality space. Each factor represents a group of correlated original variables that are uncorrelated by the other original variables that form the other factors (Hair et al., 1998). Student t-test (t-test; $p = 0.05$) was used to detect differences of factor scores between the two sampling sites (Zar, 2010). Discriminant analysis (*DA*) on the factor scores based on the generalized Mahalanobis distance was also used, to determine the morphological similarity of the shell between regions and the ability of these variables to identify correctly the specimens (Hair et al., 1998). Modularity seeks to capture the various levels and kinds of heterogeneity found in organisms, and it is considered a fundamental aspect of the biological organization. A variation module is composed of features that vary together and are relatively independent of other such sets of features (Wagner et al., 2007).

The Von Bertalanffy growth (VBGF) and mortality parameters, as well as recruitment probability and optimum exploitation rates, were estimated from the length measurements of one-year pooled data and grouped with class intervals using the ELEFAN (Electronic Length Frequency Analysis) of FiSAT software (Gayanilo and Pauly, 1997). Growth was described by the von Bertalanffy growth function (VBGF) (von Bertalanffy, 1938) $L_t = L_\infty\,[1 - e^{-K(t-t_o)}]$, where $L_t$ is the length at time t, $L_\infty$ is the length in perpetuity, e is the base of the natural logarithm, K is the rate

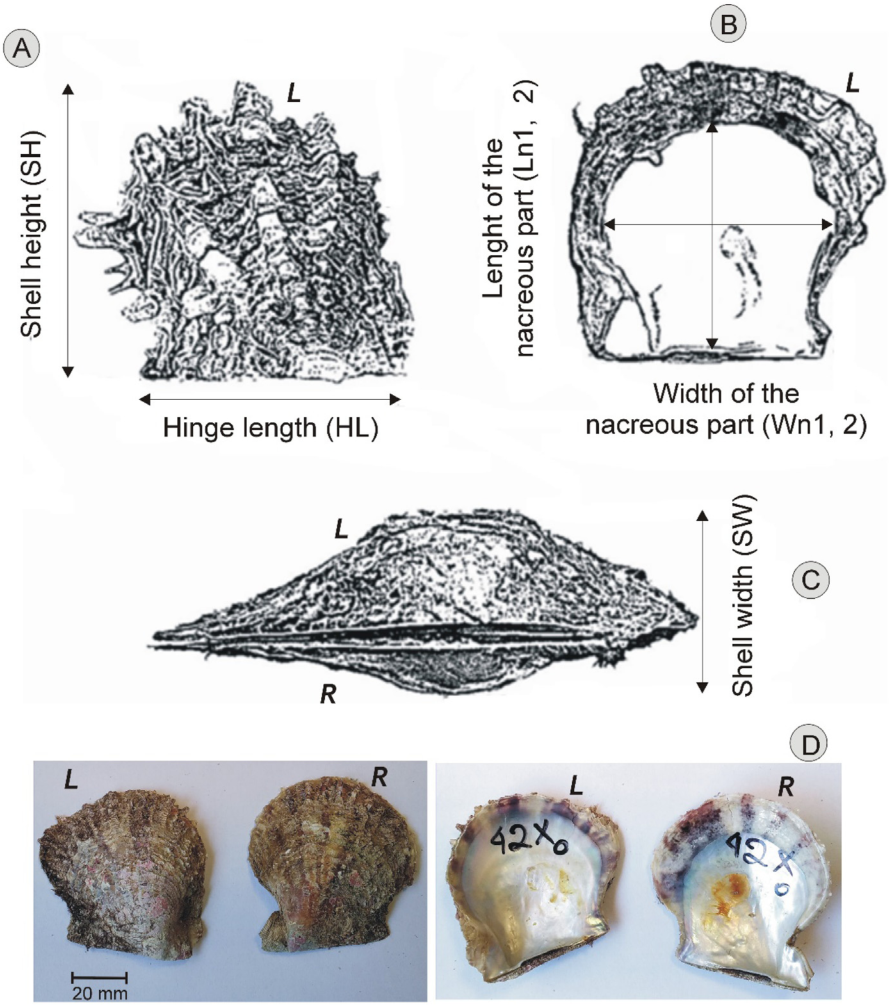

**Fig. 2.** Morphological measurements of *Pinctada imbricata radiata* shell carried out on the largest (left) valve. Measurements on the (A) external and (B) internal side of the shell, of (C) the shell thickness (adapted from Lodola et al., 2013), and (D) photo of left and right valve of shell. L: left, R: right.

with which the organism approaches $L_{\propto}$, t is the time of observation and $t_0$ the age to which the oyster belongs to zero sizes. The growth parameter K, with high values indicating low growth and vice versa, is an index of the intrinsic development rate of the species and has importance in intra-specific comparison of growth (Beverton and Holt, 1957).

The estimates of $L_{\propto}$ and K were also used to estimate the growth performance index ($\varphi'$) of the pearl oyster, as well as of the other species of the Pteriidae family using the equation $\varphi' = 2\ \mathrm{Log}_{10}\ L_{\propto} + \mathrm{Log}_{10}\ K$ (Munro and Pauly, 1983) to identify possible intra- and inter-specific differentiation among areas. Modal progression analysis was used to estimate age classes through NORMSEP method. The latter disaggregates the normal distributions that make up the frequency distribution of a sample, with the highest probability of disaggregation (Gayanilo and Pauly, 1997). The total mortality coefficient (Z) was estimated by the transformed linear curve of catches (Pauly, 1983) and natural mortality (M) was estimated from Pauly equation $\log_{10} M = -0.0066 - 0.279 \log_{10} L_{\propto} + 0.6543 \log_{10} K + 0.4634 \log_{10} T$, Pauly (1980), setting as mean annual temperature equal to 17 °C. The exploitation level (E) was estimated by the relationship $E = F/Z = F/F + M$. The recruitment pattern was obtained by projecting the length–frequency data backward on the time axis using growth parameters $L_{\infty}$ $\kappa\alpha\iota$ K (Pauly, 1986). The above method has been also used in other bivalve species, such as the case of the edible wedge clam, *Donax lubricus* in Asia (Tenjing, 2019).

The catch selectivity curve was estimated under the consideration to be similar to that of a trawl-type selection, where specimens larger than a specific size are caught entirely as long as they are in the active gear zone, while for the small size they are more likely to escape. This is because the specimens are collected by hand and the sizes caught are determined by the market value and the fisherman's ability to distinguish the smallest sizes. The effort made to collect small individuals has shown that this is quite difficult due to their low traceability to the substrate. Some young individuals were retrospectively detected when attached in specimens to older individuals. The number of specimens being in the active gear zone was calculated by performing the linear relationship of Ln (N/dt) (age) in the transformed linear curve of catches for each age class younger than the capture ages.

## 3. Results

### 3.1. Targeted interviews

In total, 16 professional fishers, all men, participated in the interview survey with a high percentage (77%) being fully dependent on fishing (i.e. the portion of their total annual income derives exclusively from fishing), whereas the rest of them (33%) was engaged in pearl oyster fishery in conjunction with agricultural activities. The interviewed fishers were experienced in pearl oyster fishery, with more than half of them having more

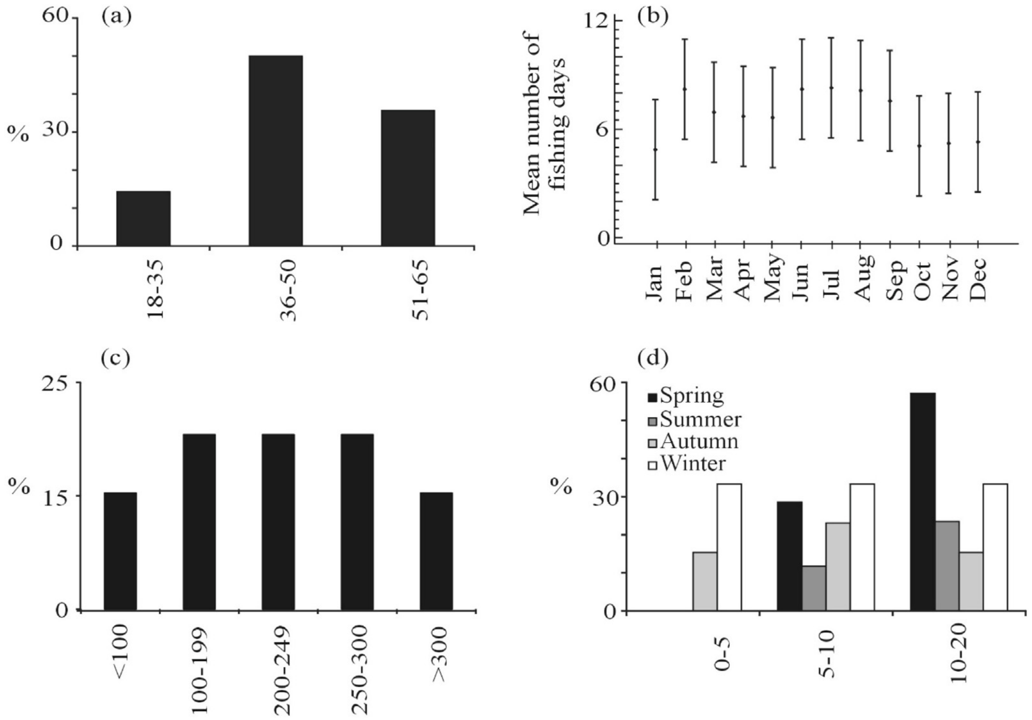

**Fig. 3.** Pinctada imbricata radiata: (a) age class distribution, (b) mean number of active fishing days per month, (c) % contribution of the mean daily catch per catch quantity category (in kg), (d) % contribution of the seasonal discard quantities from the professionals caught peal oysters in the two studied areas, the North Evoikos and Saronikos gulfs.

than 18 years of fishing experience and with the oldest fishers participating in this type of fishery since 1970. A 75% the fishers were fishing in Saronikos Gulf. The mean age of the interviewed fishers was 47 years (SD = 9.7 years) with the dominant age class at 36-50 years (50%) and ages ranging between 31 and 65 years (Fig. 3a). More than a third of the fishers (38.5%) stated that their father was engaged either exclusively or occasionally in fisheries (combined with other agricultural activities) and almost a quarter of them (23%) had a SCUBA diver father.

The mean number of fishing days per month did not show significant differences (ANOVA, $F = 1.31$, $df = 15$, $p > 0.05$) ranging from 4.90 days (SD = 1.18) in January to 8.29 days (SD = 1.18) in July with a mean annual number of fishing days equal to 6.79 (SD = 4.47) (Fig. 3b). The maximum reported number of fishing days from June to September reached 20, whereas it did not exceed 10 fishing days per month during winter. The contribution of the main fishing gear did not differ significantly ($\chi^2 = 0.81$, $df = 15$, $p > 0.05$) with season with fishing by SCUBA diver and collecting pearl oysters by hand being the most frequently fishing method used (80%) followed to a lesser extent by the use of dredges (20%).

The majority of the respondent (69.2%) stated that the daily catches of pearl oyster ranged from 100 to 300 kg, with the rest of the fishers stating maximum catches of less than 100 kg (15.4%) or more than 500 kg (15.4%) (Fig. 3c). Concerning the seasonality of the daily catches, their statements were in line with those corresponding to that of fishing days per month. Almost two-third of the respondents (63.6%) stated that the largest quantities were fished in summer, 27% of them stated during winter while the rest stated that there was no specific seasonal pattern. In line with previous answers, 63% of the respondents stated that the lowest catches of pearl oysters occurred during winter, whereas 18% during summer, and the rest considered that there was no specific seasonal pattern. Significant ($\chi^2 = 3.58$, $df = 15$, $p < 0.05$) higher number of fishers stated that discards per fishing day were higher during summer than in other seasons (10–20 kg vs. > 10 kg) (Fig. 3d). The major cause of discarding was the destroyed pearl oysters (71%), whereas the second minor cause of discarding was the small-size caught (less than 5 cm) (29%). The majority of the interviewed fishers state that the main market pathway of pearl oyster was wholesalers (70%) and to a lesser extend restaurants and local fish markets (cumulatively contributed 30%).

The majority of the fishers (60%) stated that the pearl oyster stock has been overfished, especially during the last 5 years, but almost half of the fishers (46.2%) agreed with the establishment of a temporal ban of the pearl oyster fishery, especially during its reproductive period. However, half of the interviewed fishers considered that this closure should be moved from April to June and a small percentage (17%) from June to August, whereas the rest (33%) considered that the closure should be either in winter or spring. However, a large part of the interviewed fishers (75%) considered that the local fisheries department is absent from the implementation of the fisheries legislation and more specifically from the monitoring of the fisheries control. Only a quarter of the interviewed fishers stated that occasionally pearl oyster fishery was monitored by the local veterinary office.

### 3.2. Morphometric relationships

Overall, 1083 specimens were collected in four sampling trials, 650 in the Saronikos and 433 in the North Evoikos areas. In Table 1 the descriptive statistics of each morphometric parameter and the relations among them for a sub-sample of 733 individuals (North Evoikos: 418 and Saronikos: 315). SH ranged from 15 to 100 mm (mean and SD: 64.21 and 14.91 mm) in the North Evoikos and from 15 to 97 mm (58.96 and 13.24 mm) in the Saronikos. All morphometric relations were significant ($p < 0.05$) with $R^2$ values ranging from 0.65 to 0.93, apart from the relations with the condition factor ($R^2 = 0.04$). SW exhibited positive allometry ($b > 1$; $p < 0.05$) with SH, whereas the rest of the morphometric factors and the condition factor showed negative

**Table 1**

Descriptive statistic of morphometric variables ($N_1$: individuals, Xm: mean value, SD: standard deviation, Mmn: min value, Mmx:max value) and estimated parameters relations *Ln*(Y) = a + b*Ln*(SH) of *Pinctada imbricata radiata* described in Fig. 2; $N_1$: total number of individuals, $N_2$: individuals used in morphometric analysis; a and b are the parameters of the relations and $SE_{(a)}$ and $SE_{(b)}$ are their standard errors; $R^2$ is the coefficient of determination, $t_1$: t-test for isometry, $p_1$: possibility for isometry, isom: '−': negative allometry, '+': positive allometry, $t_2$: t-test for correlation, $p_1$: possibility for non-collinearity. Codes of the variables are given in the Materials and Methods section.

| Variable (Y) | $N_1$ | Xm | SD | Mmn | Mmx | *Ln* (Y) = a + b *Ln*(SH); $N_2$ =733 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | a | b | SEa | SEb | $t_1$ | $p_1$ | isom | $R^2$ | $t_2$ | $p_2$ |
| SH (mm) | 1083 | 61.1 | 14.2 | 15.0 | 100.0 | | | | | | | | | | |
| SL (mm) | 1083 | 56.9 | 13.4 | 14.0 | 100.0 | 0.04 | 0.97 | 0.042 | 0.010 | 2.7 | 0.01 | − | 0.93 | 94.9 | 0.000 |
| HL (mm) | 1083 | 48.0 | 7.7 | 15.0 | 79.0 | 1.81 | 0.51 | 0.057 | 0.014 | 36.0 | 0.00 | − | 0.65 | 36.8 | 0.000 |
| SW (mm) | 1083 | 21.8 | 6.4 | 3.0 | 39.0 | −1.78 | 1.18 | 0.077 | 0.019 | 9.9 | 0.00 | + | 0.85 | 63.4 | 0.000 |
| Ln1 (mm) | 750 | 49.6 | 9.9 | 12.0 | 77.0 | 0.03 | 0.93 | 0.065 | 0.016 | 4.4 | 0.00 | − | 0.83 | 59.6 | 0.000 |
| Wn1 (mm) | 750 | 45.0 | 9.2 | 13.0 | 75.0 | 0.08 | 0.89 | 0.083 | 0.020 | 5.2 | 0.00 | − | 0.74 | 44.4 | 0.000 |
| Ln2 (mm) | 733 | 49.5 | 9.9 | 20.0 | 77.0 | 0.14 | 0.90 | 0.065 | 0.016 | 6.2 | 0.00 | − | 0.83 | 58.0 | 0.000 |
| Wn2 (mm) | 733 | 44.7 | 9.0 | 16.0 | 66.0 | 0.21 | 0.86 | 0.079 | 0.019 | 7.2 | 0.00 | − | 0.74 | 45.0 | 0.000 |
| TW (g) | 980 | 30.2 | 17.7 | 0.3 | 109.5 | −8.85 | 2.94 | 0.160 | 0.039 | 50.4 | 0.00 | − | 0.89 | 76.1 | 0.000 |
| FW (g) | 885 | 8.2 | 4.3 | 0.3 | 23.2 | −9.39 | 2.75 | 0.185 | 0.045 | 39.2 | 0.00 | − | 0.84 | 61.5 | 0.000 |
| SW (g) | 869 | 22.7 | 13.4 | 0.9 | 82.6 | −9.55 | 3.03 | 0.187 | 0.045 | 45.0 | 0.00 | + | 0.87 | 66.9 | 0.000 |
| CF | 869 | 36.6 | 10.5 | 11.8 | 66.9 | 4.72 | −0.28 | 0.209 | 0.051 | 25.4 | 0.00 | − | 0.04 | 5.56 | 0.000 |

**Table 2**

Results of principal components analysis (PCA), factor loadings and unstandardized coefficients for each transformed morphometric variable of *Pinctada imbricata radiata* on the four extracted factors (Fi), after varimax normalized rotation and t-test of each Fi between the two studied regions. ExpVar%: % of explained Variance, CExpVar%: Cumulative explained Variance %. Bold values indicates important values (cut-off value of ±0.5). $\overline{MFi}$: mean value and Standard deviation (SD) of factor scores of factor i per region, N is the number of individuals. Codes of the variables are given in the Materials and Method section.

| Variable | Factor loadings | | | | Variable | Unstandardized coefficients | | | |
|---|---|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | F4 | | F1 | F2 | F3 | F4 |
| | | | | | c | −129.66 | −81.02 | −15.10 | −107.09 |
| SL | 0.023 | 0.173 | 0.116 | **0.718** | SL | 0.37 | 2.77 | 1.85 | 11.44 |
| HL | 0.176 | 0.031 | −0.161 | **0.751** | HL | 2.09 | 0.37 | −1.91 | 8.92 |
| SW | 0.036 | **0.661** | −0.088 | 0.235 | SW | 0.31 | 5.77 | −0.77 | 2.05 |
| Ln1 | **0.631** | 0.192 | 0.219 | 0.217 | Ln1 | 6.72 | 2.04 | 2.33 | 2.31 |
| Wn1 | **0.704** | 0.233 | −0.003 | 0.375 | Wn1 | 5.81 | 1.92 | −0.03 | 3.09 |
| Ln2 | **0.818** | 0.162 | −0.024 | −0.142 | Ln2 | 8.72 | 1.73 | −0.26 | −1.51 |
| Wn2 | **0.828** | 0.184 | −0.136 | 0.112 | Wn2 | 7.23 | 1.61 | −1.18 | 0.98 |
| TW | 0.303 | **0.875** | 0.039 | 0.059 | TW | 1.32 | 3.81 | 0.17 | 0.26 |
| FW | 0.342 | **0.575** | **0.690** | −0.014 | FWw | 1.27 | 2.14 | 2.56 | −0.05 |
| SE | 0.416 | **0.834** | −0.158 | 0.053 | SE | 1.55 | 3.11 | −0.59 | 0.20 |
| CF | −0.148 | −0.335 | **0.897** | −0.035 | CF | −0.47 | −1.06 | 2.84 | −0.11 |
| | | | | | Region | $\overline{F1}$(SD) | $\overline{F2}$(SD) | $\overline{F3}$(SD) | $\overline{F4}$(SD) |
| Eigenvalue | 2.68 | 2.52 | 1.42 | 1.36 | Evoikos (N: 418) | 1.21(2.86) | 1.25(2.57) | −0.5(1.48) | 0.36(1.57) |
| ExpVar% | 24.4 | 22.9 | 12.9 | 12.4 | Saronikos (N: 315) | −1.61(3.11) | −1.66(2.66) | 0.67(0.96) | −0.48(1.41) |
| CExpVar% | 24.4 | 47.3 | 60.2 | 72.6 | t | 12.56 | 14.93 | 12.95 | 7.64 |
| | | | | | p | 0.00 | 0.00 | 0.00 | 0.00 |

allometry ($b < 1$; $p < 0.05$). SW showed positive allometry ($b > 3$; $p < 0.05$) about to SH, whereas TW and FW relations with SH exhibited negative allometry ($b < 3$; $p < 0.05$).

The PCA analysis extracted four factors with eigenvalues higher than one, explaining 72.3% of the variance (Table 2). PCA factor loadings of 0.50 significant positive correlations were found for: (a) factor F1 with the necreous dimensions measured for both valves (Ln1, Wn1, Ln2, and Wn2), (b) factor F2 with the weights (TW, FW and SE) and SW, (c) factor WF3 with the FW and CF, and (d) factor F4 with shell dimensions (SL and HL). Factors F1, F2, and F4 were associated with shell length and weight, whereas factor F3 with bony (bony weight and condition factor). Student t-test showed that factor loadings were significantly ($p < 0.05$) different between the two studied areas, with factors F1, F2, and F4 being higher in the North Evoikos than in Saronikos, whereas the inverse was true for F3 (Table 2).

The discriminant analysis (DA) on the factors F1, F2, and F4, apart from F3 that was excluded, due to their relation to bony weight and condition factor, exhibited one canonical variable (CaV) ($\lambda = 0.75$; $\chi^2 = 203.24$; $df = 3$; $p < 0.05$), which contributed to the initial variance. The discriminant function ($DF = 0.0229{*}F1 + 0.395{*}F2 - 0.094{*}F4$) exhibited a success rate of 75.3% and the percentage of correctly identified specimens were 75.1% and 75.5% for the North Evoikos and Saronikos, respectively.

### 3.3. *Growth analysis*

Growth and mortality parameters of the pearl oyster are presented in Table 3. The asymptotic length ($L_\propto$) and growth coefficient (K) values were found to be 100.63 mm and 103.04 mm, and 0.47 $year^{-1}$ and 0.34 $year^{-1}$, for the North Evoikos and Saronikos, respectively. The growth performance index ($\varphi'$) was found to be almost similar between the two studied areas with values of 3.67 in the North Evoikos and 3.60 in the Saronikos (Table 3). Based on length converted catch curves, total mortality coefficients (Z) were 1.92 $year^{-1}$ and 1.44 $year^{-1}$, in the North Evoikos and Saronikos gulfs, with the 95% confidence intervals overlapping between the studied areas. Natural mortality (M) was estimated at 0.62 $year^{-1}$ and 0.50 $year^{-1}$ and fishing mortality estimated at 1.30 $year^{-1}$ and 0.94 $year^{-1}$, respectively for the above-mentioned areas (Table 3). The exploitation rate was estimated at 0.68 $year^{-1}$ and 0.65 $year^{-1}$, for the two studied areas respectively.

The probability of capture for *P. radiata* in the two studied areas depicted that (upper panels in Fig. 4) the 50% of the population caught in 61.49 mm and in 55.68 mm, in the North Evoikos and Saronikos gulfs, respectively, with 100% of the individuals being caught beyond 68 mm and 65 mm. The recruitment pattern showed a similar pattern in both studied areas (lower panels in

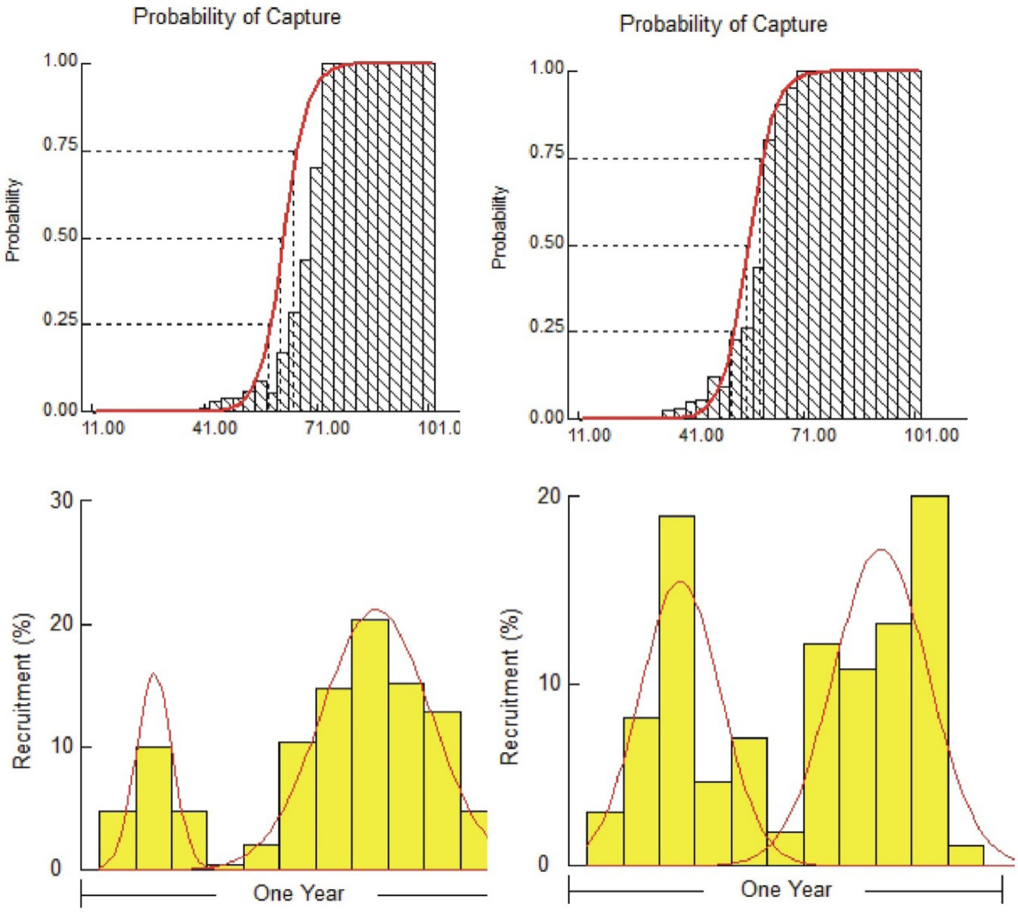

**Fig. 4.** (upper) Probability of capture and (lower) Recruitment pattern of *Pinctada imbricata radiata* caught in the two studied areas, the North Evoikos and Saronikos gulfs.

**Table 3**
Growth and mortality parameters of *Pinctada imbricata radiata* for the two studied areas (EV, N. Evoikos and SAR, Saronikos).

| Growth | EV | SAR |
|---|---|---|
| Wetherall (1986) | | |
| Asymptotic length $L_{\propto}$ (mm) | 100.63 | 103.04 |
| Z/k | 3.34 | 4.22 |
| R | −0.82 | −0.92 |
| Cut off length (mm) | 66.50 | 66.50 |
| ELEFAN I | | |
| Growth coefficient K $(y^{-1})$ | −0.47 | −0.34 |
| Growth performance index $\varphi\prime$ | 3.67 | 3.60 |
| Total mortality Z $(y^{-1})$ | 1.92 | 1.44 |
| CL95% Z $(y^{-1})$ | 1.37–2.47 | 1.32–1.67 |
| $r^2$ | 0.90 | 0.96 |
| Temperature T (°C) | 17.00 | 17.00 |
| Natural mortality M $(y^{-1})$ | 0.62 | 0.50 |
| Fishing mortality F $(y^{-1})$ | 1.30 | 0.94 |
| Exploitation rate E = F/Z | 0.68 | 0.65 |

Fig. 4), with the highest value peaking twice through a year, i.e. in March and in July.

## 4. Discussion

The integration of the information derived from *in-situ* sampling and fishers' ecological knowledge sheds light on the role of the local coastal fishery on a non-indigenous species in a data-deficient system. *Pinctada imbricata radiata* is rapidly spreading and new populations are continuously being formed and established along the shoreline of the Eastern Mediterranean (Theodorou et al., 2019). The lack of knowledge on population studies jeopardizes the ability to implement effective policies, both in terms of stock assessment and fisheries management strategies. Body size measurements, growth, mortality, and growth performance index ($\varphi'$) estimated in the present study, are used to make intra-specific comparisons of the rate of growth under different conditions (Munro and Pauly, 1983) and provide important guidelines for fishery management of the pearl oyster in the area.

In the present study, PCA revealed three variational modules (Table 2: factors F1, F2, and F4), which related to nacreous dimension, shell weight, and shell dimensions. Specimens found in the North Evoikos Gulf had a larger surface of the nacreous area, weight, length, and width of the shell, whereas the weight of the edible part and the condition factor was higher in the Saronikos Gulf. Differences in the morphological parameters, found through PCA, among the different areas have also been reported for populations located few kilometers apart (Deidun et al., 2014) to a distance of 300 km (Tlig-Zouari et al., 2010). Nevertheless, genetic data confirmed that at a geographical scale of about 50 km species populations were homogeneous (Al Saadi, 2013), indicating species morphological plasticity raised as an adaptation to the local environmental conditions (i.e. temperature, salinity, food availability, wave action, substrate type), such as those observed between the two populations in the different studied areas. Since analytical environmental data were not collected during the present study, the high level of region identification by morphometric characters as revealed by discriminant analysis (75.3%), cannot be attributed to specific environmental factors. Satellite data during the study period, November 2018–October 2019 (http://data.europa.eu/88u/dataset/10161412-a76c-42b0-b4e1-5fcccdc412b2), have shown a higher primary production in Evoikos than in the Saronikos gulfs.

In suitable habitats, specimens of *Pinctada imbricata radiata* usually achieve an average SH of 50–65 mm but may exceed 100 mm (Tlig-Zouari and Zaouali, 1994). The maximum SH recorded in this study (100 mm in the North Evoikos Gulf) is almost similar to that recorded in Tunisian coastline (100.5 mm in the Bizerta lagoon: Tlig-Zouari et al. (2009)) and higher than the largest specimen found in its native area, the Red Sea (93.2 mm; Yassien et al., 2000) as well as the one found in Sobra bay in eastern Adriatic in Croatia (maximum length of 81.1 mm: Gavrilović et al. (2017)). The species found in both studied areas can be considered as *P. imbricata radiata* species, because they consisted of larger specimens when compared with those found on Maltese islands (SH ranging from 27.0 mm and 60.8 mm; Deidun et al. (2014)) and in Linosa Island in the Sicilian Channel (SH ranging from 8.1 to 36.0 mm; Lodola et al., 2013). This is suggesting populations settled at least five years ago as indicated by the estimated life span of the species according to the present results. This is in line with the four age groups found in the Arabian Gulf (Mohammed and Yassien, 2003) in Tunisie (Derbali et al., 2019) and in Sobra bay (Gavrilović et al., 2017). Moreover, according to the fisher's statements, the presence of pearl oysters was confirmed in the area since 2010, indicating that the species has adapted well to the local conditions for almost a decade.

Between areas comparison of the growth per age class exhibited almost similar $\varphi'$ values (3.67 vs. 3.60) indicating that the growth of pearl oyster was not different among the studied areas. Table 4 gives an overview of the existing knowledge concerning shell growth rates in Pteriidae family and permits comparison. Growth parameters of the pearl oyster in Greek waters were moderate when compared with those derived from other studies worldwide (Table 4), with the highest value of $L_\propto$ (132.0 mm) recorded from Arabian Gulf (Mohammed and Yassien, 2003) and the lowest value (69.20 mm) in Egypt (Yassien et al., 2000). On the other hand, the growth rate of the pearl oyster was faster in Qatar ($K = 0.25$ year$^{-1}$; Mohammed (1994)) and lowest in Tunisie ($K = 1.75$ year$^{-1}$; Derbali et al. (2019)). Concerning the interspecific performance of growth (Table 4), the lowest $L_\propto$ and the highest growth rate were estimated for the *Pteria sterna* species in Mexico (Saucedo and Monteforte, 1997), whereas *P. margaritifera* in French Polynesia exhibited the highest $L_\propto$ value (Pouvreau et al., 2000). The other species of the Pteriidae family exhibited from moderate (*P. margaritifera var. cumingi*) to high growth rate values (*P. mazatlanica*, *P. margaritifera var. erythraensis* and *P. fucata*) when compared with that of the pearl oyster in the Mediterranean and Arabic waters (Table 4). The populations of *P. radiata* in the studied areas can be considered as well-settled taking into account that the dominant length class (50–75 mm SH) and the maximum length collected (97 and 100 mm in the two studied areas) within those values reported for describing an area as a suitable habitat for the species. Another issue that favors species settlement in the studied areas is its high tolerance to chemical contamination (Khatir et al., 2020) and its expansion in enclosed polluted ecosystems with high plankton densities (Nikolaidis et al., 2005).

The collection of individuals in depths between 0–4 m and only from mixed hard and soft substrates is as an important limitation factor of the study. The expansion of the survey in a larger range of depths/habitats is recommended to provide a conclusively guide management of a potential fishery in the entire areas, as sizes/populations can vary between habitats and depth (e.g. Derbali et al., 2011 found bigger specimens in *Posidonia* and in increased depths).

The recruitment of *P. radiata* exhibited a similar pattern in both studied areas (lower panels in Fig. 4) which peaked twice through a year, in March and in July, and is consistent with that observed in the Gulf of Gabès, Tunisie (Lassoued et al., 2018). Given that water temperature is a crucial factor for the recruitment process of *P. radiata*, in the studied areas water temperature was ranging between 12 °C and 27 °C, values which lie within suitable temperature ranges confirming spawning for *P. radiata* (from 20.6 °C to 29.7 °C in Tunisie: Derbali et al. (2009); from 15 °C to 32 °C in Qatar: Smyth et al. (2016); and from 11.7 °C to 29 °C in Croatia: Gavrilović et al. (2017)).

Total mortality estimates did not overlap between the studied areas and the probability of capture for *P. radiata* depicted that (upper panels in Fig. 4) 50% of the individuals with SH length equal or smaller than 61.49 mm and 55.68 mm, in the North Evoikos and Saronikos gulfs, respectively, was avoid fishing, whereas 100% of the individuals with SH length equal or greater than 68 mm and 65 mm were caught, respectively. The exploitation rate in the two studied areas was 0.68 year$^{-1}$ and 0.65 year$^{-1}$, respectively, which seemed to be beyond the optimum level of exploitation ($E = 0.50$). Fishers declared as a minimum commercial size that of 55 mm, whereas smaller specimens were discarded in the sea due to the low commercial value, as declared by the fishers. Although the exploitation rate values indicated that the populations in the studied areas were overexploited, the eradication of the species is unlikely, because of the high size selectivity type of the fishery and the environmental conditions of the areas. Moreover, the presence of the studied species populations in deeper zones and in other habitats (Derbali et al., 2011), where fishery is absent, could supply with new recruits the area, reducing, thus, the potential of species eradication from the studied fishery zone. Under this fishery and climate conditions the population of *P. radiata* could be sustainably exploited by the local fishers supporting their income. The need for more studies in a larger range of depths/habitats may conclusively guide management of a potential fishery in the entire areas.

Overfishing problems in pearl oyster fishery have been also confirmed by the statements of the fishers with almost half of them declaring that since the last 5 years the stock is overfished. This is indicative of the views from the professionals that during the last years, the pearl oyster fishery was not economically viable due to competition of the illegal fishery with destructive fishing methods, such as fishing with dredges using a vessel. It seemed that the exploitation pattern of the pearl oyster fishery follows the market demands with the highest fishing activity concentrated during the summer, when the demand for bivalves by the local restaurants, are highest. Consequently, the lack of a legal framework for the marketing of the species increases the illegal fishery and sale distribution. This is also confirmed by the fishers who stated that the seasonality of the fishery is strongly linked with the increasing demand from the market. In this context, the views of the fishers regarding an alternative suggested temporal ban for peal oyster fishery (April to August), were in line with the recruitment pattern of the species, which has been estimated in March and in July. In the sense of protection of the juvenile specimens (growth overfishing), it seemed that all fishers have been harmonized with the species size of recruitment and caught individuals larger than 50 mm.

Considering the double nature of the pearl oyster as an invader and shellfish product, potential restrictions on fishing activities should be focused on fisheries that cause habitat destruction, have high bycatch rates of native species, or cause injuries and/or mortalities to the local biota (Kleitou et al., 2021). The example

**Table 4**
Growth estimates of species of the Pteriidae family from other ecosystems worldwide.

| Reference | Area | L | K | $\varphi'$ |
|---|---|---|---|---|
| *Pinctada imbricata radiata* | | | | |
| Derbali et al. (2019) | Tinisia | 78.75 | 1.75 | 4.04 |
| | Tinisia | 105.00 | 0.66 | 3.86 |
| Mohemmed (1994) | Qatar | 107.00 | 0.25 | 3.46 |
| Mohemmed and Yassien (2003) | Arabian Gulf | 132.00 | 0.34 | 3.77 |
| Yassien (1998) | Red Sea | 102.30 | 0.41 | 3.63 |
| Yassien et al. (2000) | Mediterranean | 69.20 | 0.56 | 3.43 |
| Present study | Saronikos | 103.04 | 0.38 | 3.61 |
| | Evoikos | 100.63 | 0.47 | 3.68 |
| *Pinctada mazatlanica* | | | | |
| Saucedo and Monteforte (1997) | California, Mexico | 84.90 | 1.38 | 4.00 |
| *Pinctada margaritifera var. cumingi* | | | | |
| Leduc (1997) | French Polynesia, Takapoto | 175.1–177.6 | 0.37–0.42 | 4.05-4.12 |
| Pouvreau et al. (2000) | French Polynesia and Cook Islands | 160.50 | 0.46 | 4.07 |
| Pouvreau and Prasil (2001) | French Polynesia, Takapoto | 147.00 | 0.54 | 4.07 |
| | French Polynesia, Fakarava | 153.10 | 0.49 | 4.06 |
| | French Polynesia, Takaroa | 155.20 | 0.58 | 4.15 |
| | French Polynesia, Manihi | 159.60 | 0.49 | 4.10 |
| | French Polynesia, Rangiroa | 164.80 | 0.46 | 4.10 |
| | French Polynesia, Mangareva | 165.30 | 0.48 | 4.12 |
| | French Polynesia, Vairao | 186.50 | 0.42 | 4.16 |
| | French Polynesia, Tahaa-Raiatea | 178.00 | 0.50 | 4.20 |
| | French Polynesia, Ocean | 184.00 | 0.47 | 4.20 |
| *Pteria sterna* | | | | |
| Saucedo and Monteforte (1997) | California, Mexico | 68.82 | 0.12 | 2.76 |
| *Pinctada fucata* | | | | |
| Velayudhan et al. (1996) | India | 57.4–67.4 | 1.06–1.15 | 3.54-3.72 |
| *Pinctada margaritifera var. erythraensis* | | | | |
| Elnaeim (1984), recalculated by Pouvreau et al. (2000) | Red sea | 125.5 | 1.24 | 4.29 |

of blue crab *Callinectes sapidus* sets a good starting point for the management of non-endemic species in the region (Mancinelli et al., 2017), where the need to control an invasive species and mitigate its impact to the ecosystem (Bogdanoff et al., 2020), can be harmonized with the economic benefits as a fishery resource (Kleitou et al., 2021).

The adoption of such management scheme may tackle invasive species using fishing gears with high species selectivity and regulate illegal, unreported, and unregulated (IUU) fishing activities by professional and recreational fishers, issues that potentially benefiting the implementation of the recently adopted Technical Measure Regulation on sensitive species and habitats (EU REG).

## 5. Conclusions

Considering the complete lack of knowledge regarding the pearl oyster fishery in the Mediterranean, it can be assumed that the actual catches are much higher than the corresponding ones that are aggregated in the "other shellfish" category, and thus the officially reported data could be very misleading. To counterbalance this issue, the supplementary use of expert judgment opinion could provide more representative and factual information (Theodorou et al., 2020). This is because the actual impact of fisheries on the bivalve resources is hard to be evaluated by official authorities, due to misreporting estimates and serious limitations in the sampling methodology followed by the official statistical authority of fisheries data (Moutopoulos and Koutsikopoulos, 2014). Also, the landings data for bivalve species seem to be underestimated and/or unreliable, because they are largely derived from aquaculture (Theodorou et al., 2015), thus, creating a gap in the collected data, and mask potential shifts in less-resilient species. Another drawback is the misreporting of congeneric bivalve species due to the sharing of the same common name or similar taxonomic characters that are often not easy to be distinguished by non-experts. Greek fisheries target numerous bivalve species (approximately 30 species: Katsanevakis et al., 2008), while both fishers and competent authorities staff are not fully aware and thoroughly knowledgeable of the complicated relevant legislation that regulates the fisheries sector. The case of cooperation among scientists, stakeholders, authorities, and local communities must also be encouraged.

## CRediT authorship contribution statement

**Dimitrios K. Moutopoulos:** Data curation, Formal analysis, Methodology, Supervision, Writing - review & editing. **Alexis Ramfos:** Resources, Writing - original draft. **John A. Theodorou:** Visualization, Funding acquisition, Project administration, Resources, Writing - original draft. **George Katselis:** Data curation, Formal analysis, Methodology, Validation, Writing - review & editing.

## Declaration of competing interest

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

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