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RESEARCH PAPER

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Comparison of the Dynamics between Coastal and Midshore Populations of *Pinctada radiata* (Leach, 1814) (Mollusca: Bivalvia) in the Gulf of Gabes, Tunisia

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Abstract

Pinctada radiata is the first lessepsian bivalve in the Mediterranean Sea where it has been progressively expanding westwards. This comparative study provides the first insight into the population dynamics of the species by investigating the population structure, growth, mortality, and exploitation status in the coastal zone (site A; 0-1 m) and midshore area (site B; 14 m depth). The results showed that the asymptotic shell length was smaller in the coastal zone ($L\infty$ = 78.75 mm) compared to that in the midshore station ($L\infty$ = 105 mm). Growth coefficient (K) was higher in site A (1.70 yr^{-1}) than in site B (0.66 yr^{-1}). Growth performance index (Φ') values were almost similar (4.023 and 3.862) in both pearl oysters stocks. The theoretical maximum age (T_{max}) was smaller in site A (2.66 yr^{-1}) than in site B (7.05 yr^{-1}). Total mortality (Z) was estimated by length-converted catch curve at 6.18 and 1.62 yr^{-1}, fishing mortality (F) at 4.43 and 0.78 yr^{-1} and natural mortality (M) at 1.75 and 0.83 yr^{-1} for site A and site B, respectively. Recruitment was continuous and showed two major pulses in the two sampling sites.

Introduction

The marine mollusc *Pinctada radiata* (Leach, 1814) shows a widespread distribution occurring in almost all the seas of the tropical and in the subtropical regions (Al-Khayat & Al-Ansi, 2008). It was considered as one of the three non-indigenous species from the family Pteriidae distributed along the Mediterranean Sea. The other two species are *Pinctada margaritifera* (Linné, 1758) and *Electroma vexillum* (Reeve, 1857) (Zenetos et al., 2010). *P. radiata* is stated as the first lessepsian bivalve species that arrived in the Mediterranean Sea via the Suez Canal (Monterosato, 1878). This indo-pacific bivalve has successfully spread throughout the Mediterranean Sea colonizing continuously new habitats in the eastern basin (Gokoglu, Gokoglu, & Yerlikaya, 2006; Deidun, Gianni, Cilia, Lodola, & Savini, 2014) and in the Adriatic Sea and Croatian coasts (Doğan & Nerlović, 2008; Petović & Mačić, 2017).

In Tunisia, *P. radiata* has not been exploited despite its importance as a major component of the benthic fauna. Bouchon- Brandely and Berthoule (1891) in the Gulf of Gabes made the first record of this species in Tunisia.

Previous surveys highlighted the high divergence between coastal and midshore pearl oyster populations in the Gulf of Gabes using discriminant tests (Derbali, 2011), which could be related to the environmental and ecological conditions of the two bathymetric zones. Such studies are important for investigating the

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dynamics of populations as a result to their potential adaptations since a variety of different conditions (e.g., climate, temperature, salinity, wave action, available substrate, species composition, species interactions, and food sources).

Geographical patterns of species abundance may provide insights into several questions in adaptation including: what type of growth performed by the pearl oyster in the harsh environmental conditions characterizing the coastal population or in offshore area subjected to the high cover vegetation and weak currents? Does pearl oyster have ability to response to climate changes? Thus, the species' adaptations to these factors can be studied by investigating the species population parameters. As such, the various pearl oyster population dynamics should be re-examined with consideration of the bathymetric distribution.

Despite its prevalence in the literature, no empirical work has rigorously investigated the pearl oysters' population dynamics. As commercial importance of *P. radiata* increases as a candidate species for Tunisian food and pearl production, research studies focusing on its population parameters will be of considerable necessity for future economic valorisation and sustainable management of this resource in Tunisian waters. In this context and considering the above mentioned scarce information on pearl oyster's dynamics, the present study is the first attempt to estimate the population structure, growth, mortality, and exploitation rates and recruitment pattern of coastal and midshore populations.

Materials and Methods

Study Area

Kerkennah Island is located in southern Tunisian waters (10°58′-11°20′E, 34°37′-34°50′N). It is placed away from industrial activities or anthropogenic effluents. Both wide and shallow continental shelves are topographically regular. Specimens were sampled from two sampling sites, chosen with respect to depth and pearl oyster densities; the coastal zone (site A; 0-1 m depth) and the midshore area (site B; 14 m depth) (Figure 1). In site A, individuals were found on muddy sand covered in some areas by the marine seagrasses *Cymodocea nodosa* (Ascherson, 1870) and *Zostera noltii* (Hornemann, 1832). Specimens were encountered loose on the sandy bottom or attached to others mollusks. However, the midshore area is characterized by weak currents and large beds of *Posidonia oceanica* (Delile, 1813) reaching over 700 rhizomes/m^2. In some localities, the substratum was dominated by coral reefs and dead shells.

Sampling Procedure

In the two sampling sites, sampling was carried out from January to December 2010. Approximately 200 individuals were collected each month. At each site, large specimens were gathered by hand and the small ones were taken using a 2-mm mesh size sieve in a swept area of 100 m². Small individuals were found

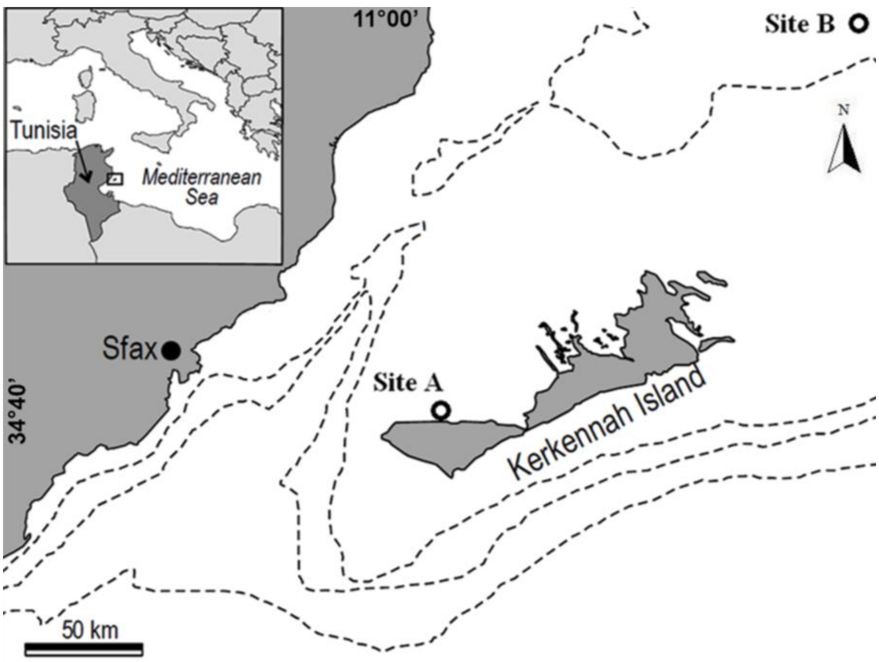

Figure 1. Geographical position of sampling sites of the pearl oyster *Pinctada radiata* in the Gulf of Gabes (Tunisia).

attached by its byssus either to oysters' shells or to solid and vertical substrates. In the midshore area, sampling was conducted by scuba diving using a small boat.

Samples were carried to the laboratory where anterior-posterior shell length (SL) was measured with a digital caliper (precision of 0.01 mm), while total wet weight (TW) was measured using a top-loading digital balance (precision of 0.001 g).

Data Analysis

Length-weight Relationships

The relationship between total weight (TW, g) and anterior-posterior shell length (SL, mm) was described by the following allometric equation:

$\log TW = \log a + b \log SL$

Where log *a* and *b* are intercept (initial growth coefficient) and slope (relative growth rate of variables) of the linear regression line, respectively. The deviation of the *b* value of the regression function from the isometric hypothetical value (b = 3) was analyzed by means of a Student's *t*-test. A significant deviation indicates a negative ($b < 3$) or positive ($b > 3$) allometric relationship.

Statistical analyses were carried out using MINITAB software (version 13, 2000). Statistical significance was considered when $P < 0.05$.

Von Bertalanffy Growth Parameters

Length-frequency data were analyzed using the FiSAT II software as explained in detail by Gayanilo, Sparre, and Pauly (2005). The asymptotic shell length ($L\infty$, mm) and the growth coefficient (K, yr^{-1}) of the von Bertalanffy Growth Formula (VBGF) were estimated from the data by means of ELEFAN-I (Electronic Length Frequency Analysis; Pauly & David, 1981; Pauly & Morgan, 1987). The VBGF is defined by the equation:

$L_t = L_\infty [1 - e^{-K(t-t_0)}]$

where L_t = mean length at age t, L_∞ = asymptotic shell length, K = growth coefficient, t = age, and t_0, the hypothetical age at which the length is zero (Pauly & David, 1981), here $t_0 = 0$.

In addition, $L\infty$ and K were used to calculate the growth performance index Φ' (Pauly & Munro, 1984) using the equation:

$\Phi' = \log(K) + 2\log(L\infty)$

Growth performance index is a topic related closely to population dynamics of benthic macro-invertebrates. This index enables comparisons of the growth performances of specimens between our two sampling sites and with other populations of *P. radiata.* The inverse von Bertalanffy growth equation was used to find the lengths of *P. radiata* at various ages.

The theoretical maximum age (T_{max}) was calculated for each population by solving for t in the von Bertalanffy equation by setting $L_t = L\infty$, using the following equation constructed by Michaelson and Neves (1995):

$$T_{max} = \frac{\ln L_\infty + Kt_o}{K}$$

Mortality and Exploitation Rate

Total mortality (Z, yr^{-1}) was estimated by length-converted catch curve method (Pauly, 1990). FiSAT calculates Z as well as the 95% confidence intervals surrounding Z based on the goodness-of-fit of the regression.

Natural mortality rate (M, yr^{-1}) was estimated using the empirical relationship of Pauly (1980):

$\log_{10} M = -0.0066 - 0.279 \log_{10} L\infty + 0.6543 \log_{10} K + 0.4634 \log_{10} T$

Once Z and M were obtained, then fishing mortality (F, yr^{-1}) was estimated using the relationship: $F = Z - M$.

The exploitation rate (E) was obtained with the relationship proposed by Gulland (1971):

$E = F/Z = F/(M+F)$

Recruitment Pattern

The routine in FiSAT reconstructs the recruitment pulses from a time series of length-frequency data to determine the number of pulses per year and the relative strength of each pulse, using the VBGF parameters (Moreau & Cuende, 1991). Normal distribution of the recruitment pattern (%) was determined by NORMSEP (Pauly & Caddy, 1985) in FiSAT.

Results

Length-weight Relationships

Relationships between logarithmically transformed data of total wet weight (TW, g) and shell length (SL, mm) of the pearl oyster *P. radiata* collected from sites A and B are shown in Table 1. At both sites, the slope (*b*) of the linear regression significantly deviated from 3 ($P < 0.05$) indicating negative allometric growth pattern.

Population Structure

Overall, 2422 and 2360 individuals of *P. radiata* were measured and their population structure studied for site A and site B, respectively (Figure 2). The shell length ranged between 6.20 – 79.00 and 7.80 – 95.15 mm for sites A and B, respectively (Table 2). The majority of pearl oyster populations were in size classes 35 - 55 and 45 - 70 mm which represented 75.76 and 67.29% of the total samples collected from the two sites,

Table 1. Regression parameters (log *a* and *b*) of shell length (SL, mm) and total weight (TW, g) relationships of *Pinctada radiata* collected from the coastal (site A) and the midshore (site B) areas in the Gulf of Gabes, Tunisia. Values of Student *t*- test (*t*) and level of significance of the deviation from the isometric value of the slope (β = 3) (*p*), coefficient of determination (r^2), SL range, TW range and number of animals examined (N) are also given, S.D. = standard deviation

Length-Weight relationship								
Sites	Log *a* ± S.D.	*b* ± S.D.	*t*	*p*	r^2	SL range	TW range	N
Site A	- 2.70 ± 0.13	2.27 ± 0.08	9.13	< 0.05	0.798	23.5 - 63.7	1.58-26.63	195
Site B	-3.48 ± 0.07	2.75 ± 0.04	6.25	< 0.05	0.956	16.45-101	0.81-121.5	217

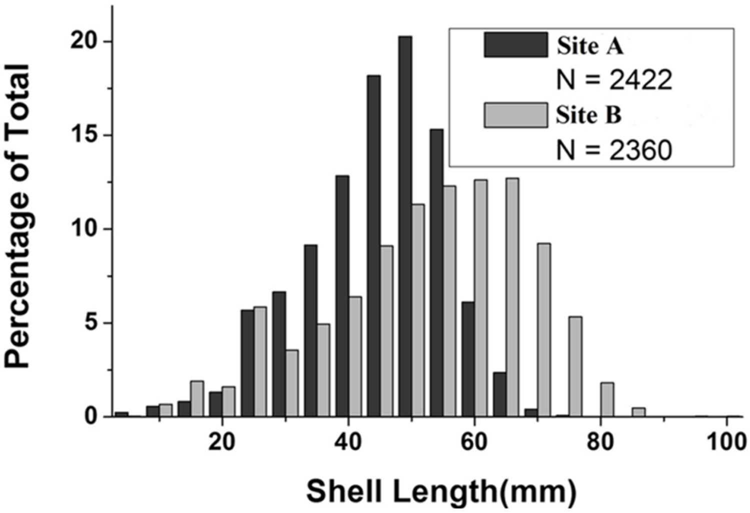

Figure 2. Variations in the percentage occurrence of the different size classes of *Pinctada radiata* collected from site A and site B throughout the study period. N=number of oysters examined.

Table 2. Population parameters of *Pinctada radiata* collected from coastal and midshore populations in the Gulf of Gabes, southern Tunisia

Population parameters	Coastal population	Midshore population
Asymptotic length ($L\infty$) in mm	78.75	105.00
Growth co-efficient (K) yr^{-1}	1.70	0.66
Growth performance index (Φ)	4.023	3.862
The theoretical maximum age (T_{max}) yr^{-1}	2.66	7.05
Natural mortality (M) yr^{-1}	1.752	0.836
Fishing mortality (F) yr^{-1}	4.43	0.78
Total mortality (Z) yr^{-1}	6.18	1.62
Exploitation rate (E)	0.72	0.48
Shell length (SL) range (mm)	6.20 – 79.00	7.80 – 101.00
Sample number (N)	2422	2360

respectively. Large individuals (> 70.00 mm) constituted 0.49 and 16.95% of total samples collected from site A and site B, respectively.

Growth Parameters

Estimated asymptotic length ($L\infty$) and growth coefficient (K) of the von Bertalanffy Growth Formula (VBGF) by ELEFAN-I were 78.75 mm and 1.700 yr^{-1} and 105.00 mm and 0.660 yr^{-1} for pearl oysters collected from site A and site B, respectively (Figures 3-4 and Table 2). Figures 3 and 4 show length frequency distributions and the superimposed growth curves estimated by ELEFAN-I for *P. radiata* collected from site A and site B, respectively. Growth performance index calculated with the parameter estimates from ELEFAN-I (Φ) was 4.023 and 3.862 in site A and site B, respectively (Table 2).

Age and Growth

The sizes attained by the coastal pearl oyster population were 64 and 76 mm at the end of 1st and 2nd years of age, respectively (Figure 5). For the midshore population, the sizes attained were 50.71, 76.96, 90.51, 97.54, and 101.12 mm at the end of 1st, 2nd, 3rd, 4th and 5th years of age, respectively (Figure 5). Therefore, the average growth rate of *P. radiata* through the 2nd year of life was shown as similar values; 76.13 and 76.96 mm. yr^{-1} for site A and site B, respectively. However, the theoretical maximum age (T_{max}) was higher in site B (T_{max} = 7.05 yr^{-1}) than in site A (T_{max} = 2.66 yr^{-1}) (Table 2).

Mortality and Exploitation Rate

Length-converted catch curve analysis allowed to estimate total mortality (Z) for *P. radiata* 6.18 yr^{-1} for site A and 1.62 yr^{-1} for site B (Table 2). The linearized catch curves utilized in the estimation of Z are presented in Figures 6 and 7 for the two sites, respectively. The darkened circles represented the points used in calculating Z via linear regression analysis. For the coastal population, the intercept (*a*) and slope (*b*) ±S.D. of the regression line on the selected data points were 11.69 ± 1.09 and -6.18 ± 0.78, respectively. For the midshore population, the intercept (*a*) and slope (*b*) ±

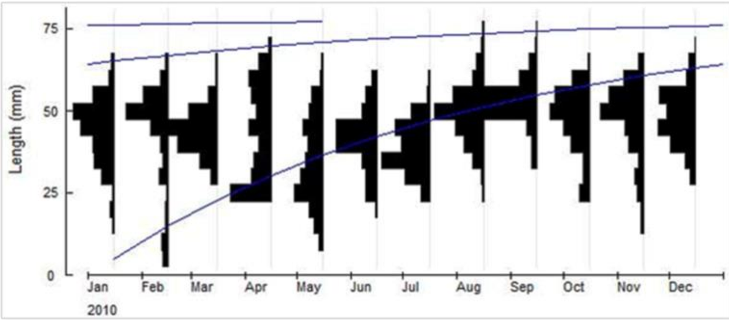

Figure 3. Length-frequency plot of *Pinctada radiata* samples taken from site A with superimposed growth curves estimated by ELEFAN 1 ($L\infty$ = 78.75 mm and K= 1.700 yr^{-1}).

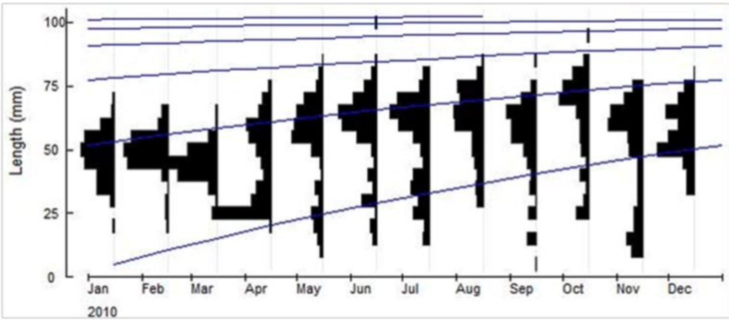

Figure 4. Length-frequency plot of *Pinctada radiata* samples taken from site B with superimposed growth curves estimated by ELEFAN 1 ($L\infty$ = 105.00 mm and K= 0.660 yr^{-1}).

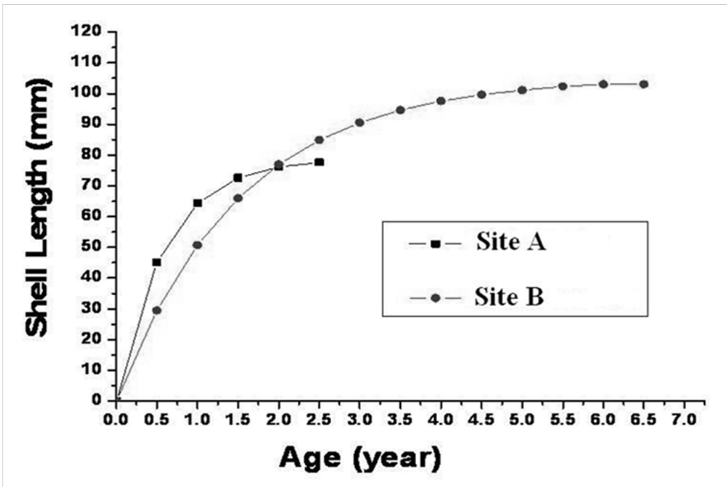

Figure 5. von Bertalanffy growth curves in terms of size at age based on the growth parameters estimated from ELEFAN-I for *Pinctada radiata* collected from site A and site B.

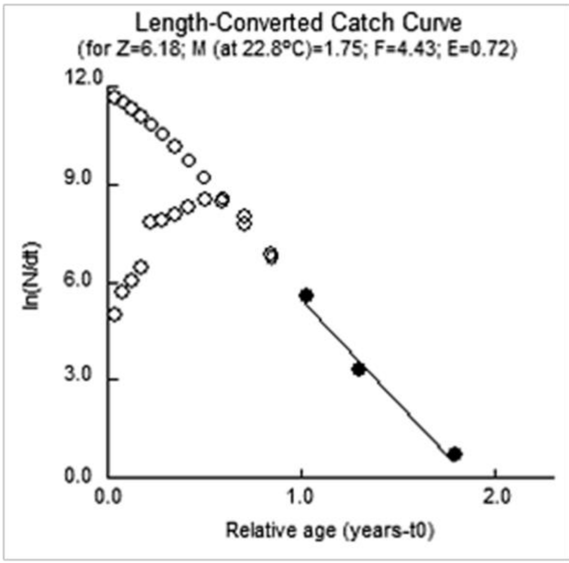

Figure 6. Length converted catch curve of *Pinctada radiata* collected from site A.

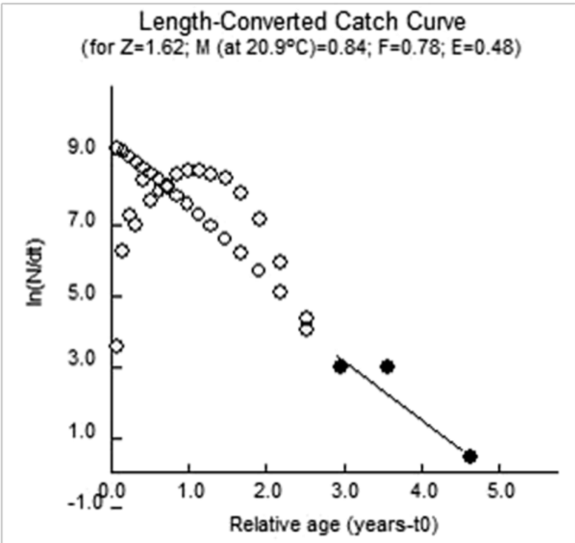

Figure 7. Length converted catch curve of *Pinctada radiata* collected from site B.

S.D. of the regression line were 7.17 ± 2.39 and -1.62 ± 0.63, respectively.

Estimated value of natural mortality (M) from Pauly's empirical formula was higher (1.75 yr^{-1}) for site A than site B (0.84 yr^{-1}). Fishing mortality (F) was estimated to be 4.43 and 0.78 yr^{-1} for the two sites, respectively (Table 2). The rate of exploitation (E) was estimated at 0.72 for site A and 0.48 for site B (Table 2).

Recruitment Pattern

The recruitment patterns (%) generated by FiSAT for *P. radiata* for the two sites were continuous throughout the year with two major pulses. For site A, the relative strength of the pulse was 6.07 and 27.70 % recruitment in February and August, respectively (Figure 8). For site B, the relative strength of the pulses were 13.64 and 13.94 % recruitment in April and August, respectively (Figure 9).

Discussion

The present study provided new information about the population structure, growth, mortality, and exploitation rates and recruitment pattern of pearl oyster populations at two different depth zones in Kerkennah Island (Gulf of Gabes). Mean shell length seems to be a good indicator for biomass, production and stock assessment estimates as already reported in *P. radiata* (Derbali, Jarboui, Ghorbel, & Dhieb, 2009; Deidun et al., 2014) and in other bivalves (Kandeel, 2008; Zeinalipour, Hasanzadeh Kiabi, Reza Shokri, & Ashja Ardalan, 2014; Kandeel, Mohammed, Mostafa, & Abd-Alla, 2017). In this study, we can report that, as the

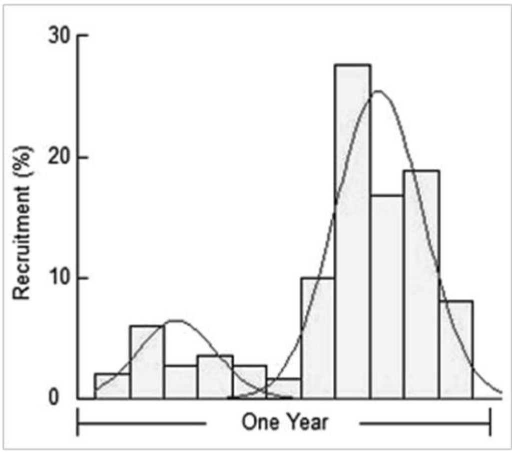

Figure 8. Predicted recruitment pattern of *Pinctada radiata* population in site A.

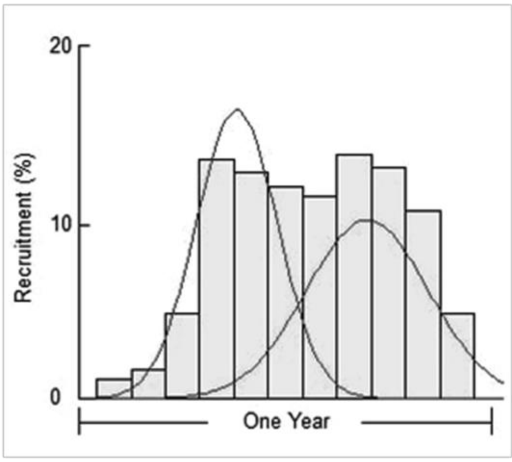

Figure 9. Predicted recruitment pattern of *Pinctada radiata* population in site B.

pearl oyster grows, its weight increases at a slower rate than its length in sites A and B. These variations in the morphometric relationships between localities can be related to environmental factors such as depth and sediment type. For example, Bellaaj-Zouari, Dkhili, Gharsalli, Derbali, and Aloui-Bejaoui (2012) showed that low tides marks might affect the morphology of *P. radiata* individuals.

The positive correlation between size and depth has previously been reported in the study area (Derbali, 2011). *P. radiata* was encountered from intertidal zone to 40 m depth, with a highest population density (145 inds/m^2) recorded at depth range of 2-20 m. Sexton, McIntyre, Angert, and Rice (2009) showed that physical and ecological factors controlling distributional ranges of the species have received heightened attention due to anticipated climate change and increased biological invasions.

Morphological differences from different environments have previously been reported for bivalves (e.g. Yoshino, Katano, Hayami, Hamada, & Kobayashi, 2013; Diederich et al., 2015). As such, pearl oysters may have a mechanism that compensates for reduced feeding time, this could potentially limit their densities, especially if slower growth delays a potential escape in size from mortality in the intertidal zone (Hunt & Scheibling, 1997). Though other filter feeders may periodically stop feeding while submerged (e.g., Cranford, Ward, & Shumway, 2011), it is unknown what would cause *P. radiata* to perform in this way while under water in ideal conditions (e.g., normal salinity, oxygen, and temperature, and no predators). It seems that the maximum size (95 mm), recorded in deeper waters site, is larger than that observed by Seurat (1929) (85 mm) in El Bibane Lagoon and Tlig-Zouari (1993) in the Kerkennah Islands (74 mm). This maximum size is also larger than that recorded by Yassien (1998) and Yassien, Abd EL-Razek, and Kilada (2000) in the Red Sea (93.2 mm) and eastern Mediterranean Sea (64 mm), respectively. Nevertheless, it is smaller than that recorded by Tlig-Zouari, Rabahoui, Irathni, and Ben Hassine (2009) along the northern and eastern Tunisian coasts (100.5 mm).

The asymptotic shell length ($L\infty$) derived from the coastal population was smaller than that of the midshore population. Differences in populations' distribution and in growth have been assumed in discussions of evolutionary hypotheses including theoretical studies of the species life-history strategies in their habitat. Differences in the growth parameters of pearl oyster in the present study and other studies (Table 3) might be due to differences in the ecosystems investigated and the responses of species to environmental gradients. Saeedi, Ardalan, Kamrani, and Kiabi (2010) have suggested several key factors affecting growth at the local scale in bivalves inhabiting the northern Persian Gulf including individual's difference, climate, latitude, and longitude.

The negative correlation between $L\infty$ and K invalidates comparison based on individual parameters (Pauly & Munro, 1984). As a result, comparison of the growth performance of population of bivalves is better fitted by the growth index phi prime (Φ'). This criterion was used to characterize not only similar species (Pauly & Munro, 1984), but also related species as in the case of scallops (Del Norte, 1988). On comparison, Mohammed and Yassien (2003) estimated $L\infty$ for *P. radiata* in Qatari waters as 107.0 mm and K as 0.25 y^{-1}. Yassien (1998) calculated $L\infty$ = 95.74 mm and K = 0.41 y^{-1} for the same species in the Red Sea. Yassien et al. (2000) estimated $L\infty$ as 69.18 mm, and K as 0.56 $y^{-1}$for *P. radiata* in the eastern Mediterranean. These differences can be explained by the different methods applied for age determination. Also, it can be explained by the different survival strategies and ecological factors present at different latitudes.

The data presented here confirm that *P. radiata* is a fast-growing species. On comparison, obtained values are higher than that reported by Mohammed (1994), Yassien (1998), Yassien et al. (2000), and Mohammed and Yassien (2003). On the whole, nonlinear growth functions such as the VBGF are difficult to compare, and some authors (e.g., Herrmann, 2009) have demonstrated the suitability of composite indices of overall growth performance for comparisons for various clam species. Both coastal and midshore populations from study area exhibited higher growth performance. It can be assumed that food availability is a principal factor affecting growth and aspects of population dynamics such as production, reproduction, recruitment and mortality.

Total mortality rate of *P. radiata* at the coastal site was higher than at the midshore site, and fishing mortality for midshore pearl oysters was lower than that for coastal ones. We can speculate that the higher fishing mortality at the coastal zone might be attributed to the commercial harvesting of the shellfish, *Venerupis decussata* (Linnaeus, 1758) and *Hexaplex trunculus* (Linnaeus, 1758) and to the other different fishing activities. In the same way, natural mortality reported for coastal pearl oysters was higher than that estimated for the midshore area. This might be attributed to the anthropogenic activities (e.g. habitat modification and habitat degradation). Earlier studies have shown that commercial harvesting can reduce the fitness of bivalves on intertidal areas leading to their higher mortality (Robinson & Richardson, 1998).

Salinity may be the main factor affecting pearl oyster abundance in the inshore area. It reached high values in the study area ranging between 31.8-48.6‰ and 30-48‰ at site A and site B, respectively (Derbali, 2011). For other bivalve species, Boyden and Russel (1972) stated that maximum age was reduced within hypersaline environments. On the whole, the coastal zone is associated with reduced performance (i.e., feeding rate) in some marine invertebrates (e.g., Miller, Harley, & Denny, 2009). The pattern of size distribution (midshore > coastal) in *P. radiata* suggests that coastal individuals could be stressed in relatively poor physiological condition compared to midshore individuals. Similar events were reported for the gastropod species *Crepipatella peruviana* (Lamarck, 1822) readily found both intertidally and subtidally in Chile waters (Diederich et al., 2015). Coastal *P. radiata* population may of course have physiological adaptations for maximizing energy gain that we did not quantify in this study.

Recruitment of *P. radiata* in the two sites was year-round and exhibited two major pulses. This pattern of recruitment is typical for tropical bivalves, which are fast-growing and short-lived species (Del Norte, 1988; Mohammed & Yassien, 2003; Del Norte-Campos, 2004; Kandeel et al., 2017). However, recruitment pulses were not found to be correlated with the spawning pattern in the study areas, as previous findings have demonstrated that this species displayed a clearly defined annual

Table 3. Values of von Bertalanffy growth parameters (*K* and $L\infty$) and growth performance indices (ϕ') of *Pinctada radiata* in different localities; ϕ' = log K + 2 log $L\infty$

Locations	$K\ yr^{-1}$	$L\infty$ (mm)	ϕ'	References
Coastal population, Gulf of Gabes, Tunisia	1.70	78.75	4.023	Present study
Midshore population, Gulf of Gabes, Tunisia	0.66	105.00	3.862	Present study
Qatari waters, Arabian Gulf	0.34	132.18	1.77	Mohammed (1994)
Qatars waters, Arabian Gulf	0.25	107.00	1.456	Mohammed & Yassien (2003)
Eastern Mediterranean, Egypt	0.56	69.2	1.428	Yassien *et al*. (2000)
Red Sea, Egypt	0.41	102.3	1.637	Yassien (1998)

reproductive cycle with two peaks occurring in summer and autumn (Derbali, 2011).

Finally, the peal oyster *P. radiata* is an extremely successful invasive species in Tunisian waters due to its ability to perform well in the not preferred living conditions that characterize the coastal zone. Our findings focused on the pearl oyster populations' dynamics in two different ecological sites could be a crucial baseline to assess their stock. The data may help to determine future quantitative changes indicating trends in Tunisian waters that are exposed to various factors of environmental conditions and human activities. Further studies are needed to explore the association between spawning and recruitment for *P. radiata* with environmental variables. Also, genetic investigations are required to understand the relative abilities to invade new areas.

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