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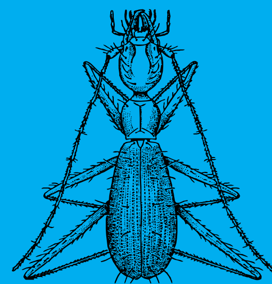

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Research Article

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Recovery of *Flexopecten glaber* (Linnaeus, 1758) (Bivalvia: Pectinidae) in the Bulgarian Black Sea Waters: Recent Distribution, Population Characteristics and Future Perspectives for Protection and Commercial Utilisation

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Abstract: In 2021, an abundant adult population of *Flexopecten glaber* was found in the Bulgarian Black Sea waters for the first time since the 1960s. The study provides original information on the distribution, habitat preference and population characteristics: size and age structure, growth coefficients, mortality, condition index and meat yield. The remarkable recovery and expansion of *F. glaber* is explained with the Black Sea recovery from eutrophication, reduced predatory pressure from the declining population of *Rapana venosa* and changing climatic conditions. The perspectives for the development of a new type of shellfish mariculture in the Bulgarian Black Sea waters are discussed.

Key words: size and age structure, growth parameters, mortality, condition index

Introduction

The smooth scallop *Flexopecten glaber* (Linnaeus, 1758) is a Mediterranean species that colonised the Black Sea c. 5–7 thousand years ago, after the Holocene reconnection of the Neoeuxinian Lake to the global ocean system via the Bosporus and Dardanelles Straits (Neveskaya 1965, Bondarev 2018). The scallop in the Black Sea was considered to be a distinct subspecies, *F. glaber ponticus* (Bucquoy, Dautzenberg & Dollfus 1889), of the Mediterranean scallop *F. glaber* (Bucquoy et al. 1889). Sometimes, it has been recognised as a distinct species, *Flexopecten ponticus* (see Scarlato & Starobogatov 1972). More recently, the results of a morphological and DNA barcoding studies (Slynko et al. 2020) identified the Black Sea form as identical with the Mediterranean populations, i.e. as *F. glaber* (see Bondarev 2018).

Flexopecten glaber used to be rare in the Bulgarian Black Sea waters during the first half of the 20th Century and the available historical data suggest its probable extinction since the 1960s. In 2021, an abundant adult population of *F. glaber* was found along the Bulgarian Black Sea coast during marine monitoring surveys. The current study provides information on the distribution and the population characteristics of the smooth scallop off the Bulgarian coast. We discuss the possible environmental conditions that could have contributed to the species recovery as well as the conservation and exploitation challenges to its sustainable management.

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Materials and Methods

The materials of *F. glaber* were collected in August 2021 on board of FV Elis using beam trawl with width 4 m and mesh size 2 cm. Trawling operations were carried out at depth 16–48 m at 15 locations along the Bulgarian Black Sea coast (Fig. 1). Further, three samples were collected with Van Veen grab (0.05 m^2) on board MV Nomad at depth 32–38 m (Fig. 1). The specimens sampled by the trawl or by the grab were counted and measured with a ruler with precision to the nearest 1 mm, then released to the sea. One qualitative sample containing the entire catch of 325 specimens was retained for laboratory analyses of the population characteristics at the southernmost sampling site near Tsarevo Town (Fig. 1).

In the laboratory, the morphological characteristics height (H) and length (L) of the shell were measured with digital calliper to the nearest 0.01 mm. Measurements were taken only from the larger left (upper) shell. The shell length and height datasets were divided into size classes of 2 mm intervals. The total wet weight (TW), meat wet weight (MW) and shell weight (SW) were determined with digital scales with accuracy 0.0001 g. The overgrowing barnacles, bryozoans and polychaetes as well as the shell cavity water were removed before weighting.

Age was estimated from distinct annual growth rings on the left (upper) shell formed during winter (Gosling 2003). The relationship of shell length to shell height as well as shell height to total weight and meat weight were determined according to the allometric equation:

$$y = a*x^b \qquad (1),$$

using the least square regression analysis available in Microsoft Excel.

The von Bertalanffy growth function was fitted to size-at-age data of 312 individuals (13 individuals were not aged due to indistinct growth rings), according to the equation:

$$H_t = H_\infty *(1 - e^{-K(t-t_0)}) \text{ [mm, y]} \qquad (2),$$

where H_t is the height at age t, H_∞ is the theoretical maximum size attained under specific environmental conditions, K is a growth constant reflecting the rate, at which the maximum size H_∞ is approached, and t_0 is the theoretical age, at which shell height equals zero.

The total mortality rate Z was estimated from the equations in Beverton & Holt (1956) and Ault & Ehrhardt (1991):

$$Z = K * \frac{H_\infty - \overline{H}}{\overline{H} - H'} \qquad (3),$$

where K and H_∞ are the parameters of the von Bertalanffy equation, H is the mean shell height and H' is the minimum shell height in the catch.

$$\left(\frac{H_\infty - H_{max}}{\overline{H} - H'}\right)^{z/k} = \left(\frac{A(H')}{A(H_{max})}\right) \qquad (4)$$

$$A(H') = z(H' - \overline{H}) + k(H_\infty - \overline{H})$$

$$A(H_{max}) = z(H_{max} - \overline{H}) + k(H_\infty - \overline{H}),$$

where $\overline{H}$ is the average height of the shell, H' – the smallest size class observed in the sample and H_{max} – the largest size class observed in the sample.

The condition index (CI) was calculated according to the equation:

*CI = (Meat weight [g]/Shell weight [g]) * 100* (5)

The meat yield (MY) was determined according to the equation:

*MY= (Meat weight [g]/ Total weight [g]) * 100* (6)

The average CI and MY were calculated for the height class ranges: 20–24, 26–30, 32–36, 38–42 and 44+ mm. One-way ANOVA was used to test if there was significant difference of CI and MY at different size.

Results

Smooth scallops were found at 18 locations on a variety of substrates: muddy sand, sandy mud, shelly coarse and mixed sediments as well as on mussel beds at depth range 16–48 m. In order to protect the valuable species from the potential threat of unregulated harvesting, the precise locations are considered sensitive information and, therefore, their coordinates are not disclosed. The established geographical range stretched from south of Tsarevo Town to north of Durankulak Village (Fig. 1).

Seven colour morphs were identified: off-white, brown, violet, orange, pink, yellow and multi-coloured with bands and spots of two or three pigments (Fig. 2). The most abundant form was off-

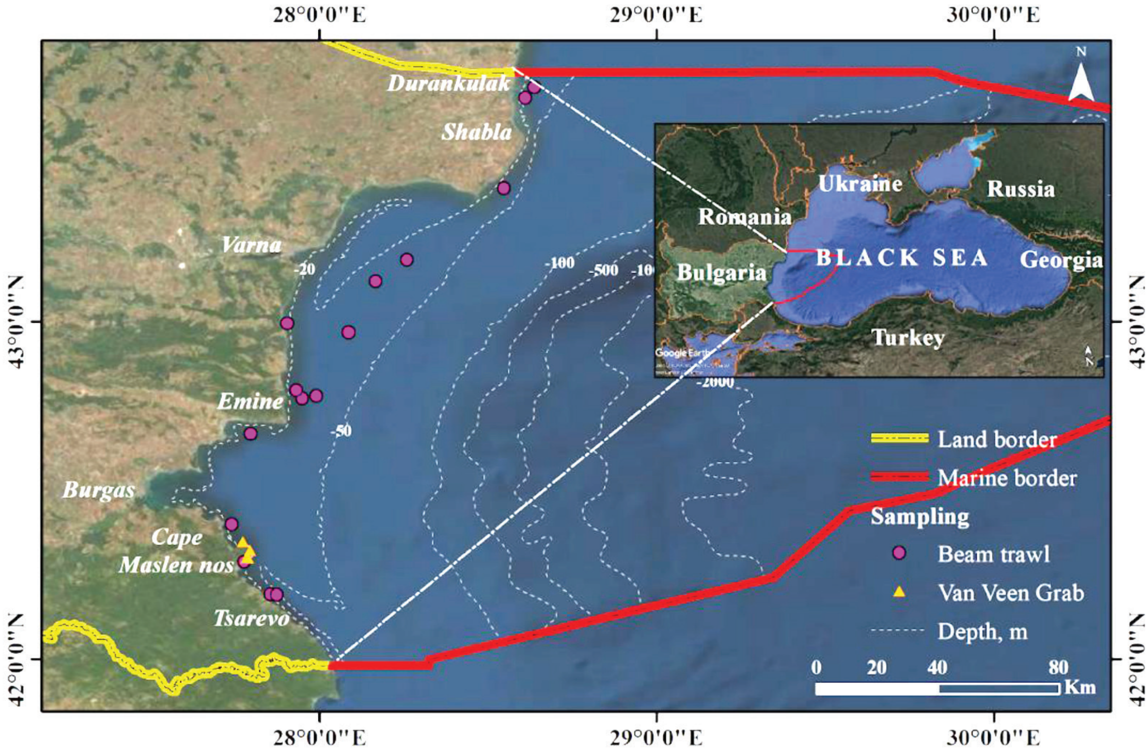

Fig. 1. Map of the study area and sampling locations of *Flexopecten glaber* from the Bulgarian Black Sea waters.

Fig. 2. Shells of *Flexopecten glaber* demonstrating colour variations of specimens from the Bulgarian Black Sea waters.

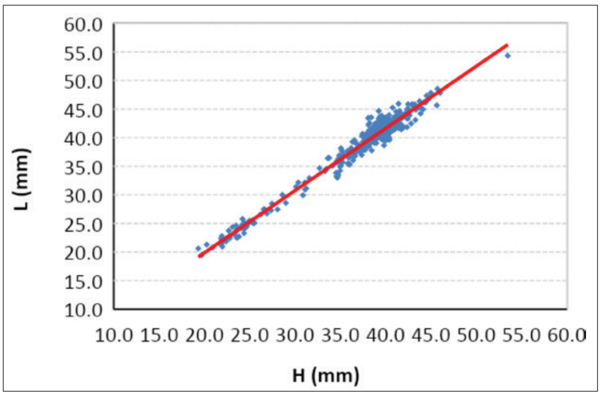

Fig. 3. Relationship of length (L) to height (H) of *Flexopecten glaber* from the Bulgarian Black Sea waters.

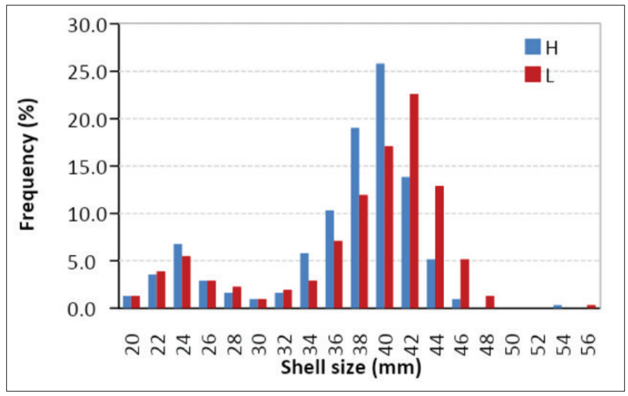

Fig. 4. *Flexopecten glaber* size frequency distribution (2 mm height (H) and length (L) classes, N = 325) of a sample taken from the scallop bed near Tsarevo town.

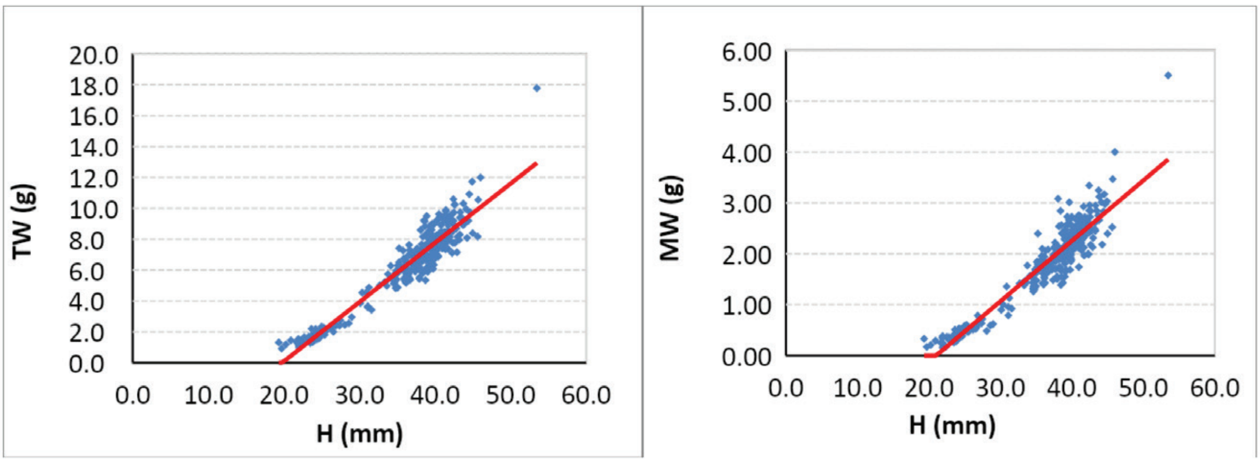

Fig. 5. Total weight (TW) and meat weight (MW) to shell height (H) relationships of *Flexopecten glaber* from the Bulgarian Black Sea waters.

white while the yellow form was very rare.

The shell valves were usually longer than high and rarely higher than long. The relationship between the two size variables, H and L, was described by the allometric equation. For the examined scallop population the growth coefficient b was close to unity (b=1.06) or nearly isometric (Fig. 3). Nevertheless, the shell length increased slightly faster than the height, i.e. a positive allometry that suggested differential growth vectors operating at different points around the mantle edge playing a key role in shell secretion.

The shell length ranged between 19.43 and 54.34 mm, and the shell height – between 19.33 and 53.48 mm. The size-frequency distribution was polymodal and dominated with >75% by large individuals with H > 36 mm (Fig. 4). The first distinct mode corresponded to the 1+ year age class, while the second mode was composed of the overlapping 2 to 7 year age classes. The largest specimen found was separated by couple of size classes from the second mode and was estimated at 9 years old.

The total wet weight ranged between 0.91 and 17.78 g, and the meat weight was between 0.15 and 5.51 g. The total weight and meat weight to height relationships were described by allometric equations with the growth coefficient below and above 3, respectively (Fig. 5). The results suggest that the soft tissues grow relatively faster (positive allometry) than the total weight (negative allometry) of the scallops in relation to their height. That has implications for the CI and MY, which increased with height (Fig. 6).

The average CI was 39.0 % ± 6.6 SD and the average MY was 27.9 % ± 3.5 SD for aggregated size classes. The average CI increased significantly (ANOVA, $p < 0.001$) with size: from 29.2 % for the

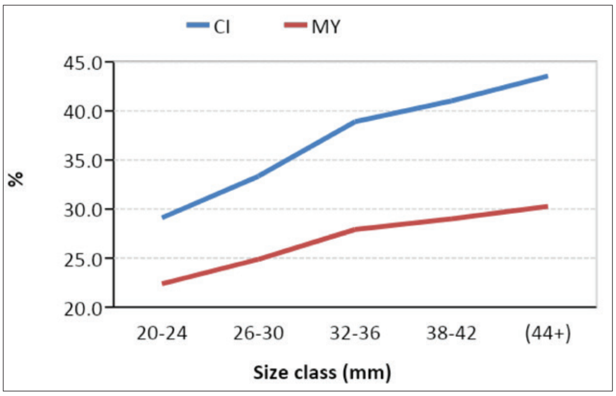

Fig. 6. Average condition index CI and meat yield MY per size classes of shell height of *Flexopecten glaber* from the Bulgarian Black Sea waters.

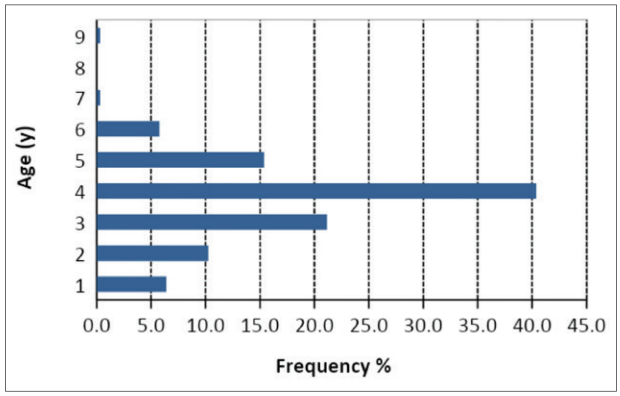

Fig. 7. Age structure of *Flexopecten glaber* from the Bulgarian Black Sea waters.

aggregated H classes 20-24 mm to 43.6 % for H classes 44+ mm (Fig. 6). The average MY also increased significantly (ANOVA, $p < 0.001$) from 22.4 % to 30.3 % for the respective size classes (Fig. 6).

The age structure had irregular distribution with over 40 % of the population abundance belonging to the predominant age class of 4 years (Fig. 7) and decreasing abundance towards younger classes of 3-1 years and elder classes of 5-7 years. This structure could have resulted from either harvesting selectivity or stochastic recruitment year to year, or due to depth segregation of juvenile and adult individuals in the population.

Size-at-age data of 312 specimens were fitted best by the von Bertalanffy equation (Fig. 8):

$$H_t = 54 \text{ mm} * (1 - e^{-0.24(t+1.3)})$$

Clearly, the largest specimen found (H = 53.48 mm, age = 9 y) did not fit well the growth function. Incorrect age determination had been possible for that particular specimen due to difficulty to distinguish well the latest annual bands at the shell margin.

The total mortality was calculated at Z = 0.24 $year^{-1}$ by Beverton & Holt (1956) and at Z=0.231 $year^{-1}$ by Ault & Ehrhardt (1991) methods. Since there has been no commercial harvesting of the scallops to date, the total mortality could be regarded as equal to the natural mortality only.

Discussion

In the beginning of the 20^{th} Century, *F. glaber* used to have abundant and commercially harvested populations along the Crimean coast and in the Sevastopol Bay, together with the smooth oyster (Milashevich 1916). Until the middle of the previous century,

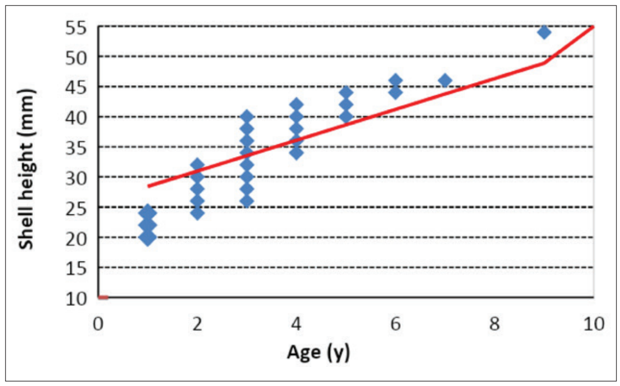

Fig. 8. Von Bertalanffy growth function fitted to 312 size-at-age data pairs of *Flexopecten glaber* from the Bulgarian Black Sea waters: H_∞ = 54 mm, K = 0.24, t_0 = - 1.3 (N = 312).

the smooth scallop was a dominant species in the biocoenosis of *Chlamys–Ostrea* as well typical for other biocoenoses at depth 3–40 m (Nevesskaya 1965). Towards the beginning of 1990s, the scallop disappeared from its previous range and was listed in the Red Lists of Crimea (Revkov 2015) and Sevastopol (Revkov 2018). More recently, the scallop re-appeared at sites where it had not been found during the previous 20 years (Bondarev 2018, 2019, Slynko et al. 2020, Shcherban & Melnik 2019).

The historical records of *F. glaber* in the Bulgarian Black Sea are rare. Chichkoff (1912), Borcea (1931) and Caspers (1951) observed few specimens or fresh shells at Balchik, Varna Bay, Nesebar, Pomorie, St. Anastasia Island and Sozopol. Kaneva-Abadjieva (1960) examined samples collected in the 1950s and reported that scallops were found more commonly along the southern coast of the Bulgarian Black Sea at depth down to 40 m; the specimens had maximum sizes of L = 43.5 mm and H =

41 mm. No further records have been published. It appears that *F. glaber* was infrequent and then probably disappeared since the 1960s from the Bulgarian Black Sea waters. The authors of this study had not observed live specimens of the species during their 30-year professional careers in marine biology and around a thousand samples collected in the same study area. Recently, unpublished sightings in Sozopol Bay on reefs and artificial hard substrate, i.e. a shipwreck at around 16 m depth (D. Berov, personal communication) and along Byala coast (social networks 2020) inferred a possible recurrence of the smooth scallop in Bulgarian waters.

This study detected a very prominent recovery of *F. glaber* population along the most part of the Bulgarian Black Sea coast, from Tsarevo Town on the south to Durankulak Village on the north. The expansion has probably taken place over the previous decade (2010s) but has remained undocumented until 2021.

The habitat preference of *F. glaber* in the Bulgarian Black Sea encompasses a wide range of sediments including muddy sand, sandy mud, shelly gravel and mixed sediments at depth range 16–48 m. The smooth scallop was observed also on rocky reefs and artificial hard substrate (D. Berov, personal communication). In recent years, a well-developed local population was found in *Zostera noltei* seagrass meadows in Kazach'ya Bay (Crimean Peninsula) at depth 1–6 m (Bondarev 2020). Many specimens were also collected from the mouth of Donuzlav Bay (Crimean Peninsula) at depth 12–15 m (Slynko et al. 2020) and from oyster collectors in Karantin Bay (Crimean Peninsula) at depth 4–5 m (Shcherban &Melnik 2019). Individual specimens were found on shelly gravel and coarse sand in Mangalia area of Romania (Filimon 2020). Utilization of various environments describes *F. glaber* as a habitat generalist but shelly gravel appears to be the best suited for the species due to its affinity to attach by byssus to shells. The current finding of *F. glaber* at 48 m is its lowest depth boundary documented to date in the Black Sea. The first certain findings of live specimens in the Romanian waters and the extended depth range in the Bulgarian Black Sea suggest a distribution range extension of this species.

The observed recovery and expansion of *F. glaber* around the Black Sea is possibly associated with environmental recovery from eutrophication, reduced predatory pressure from declining *Rapana venosa* population and changing climatic conditions (warming). The smooth scallop is very sensitive to dissolved oxygen deficiency (Nevesskaya 1965); therefore, eutrophication driven hypoxia could have contributed to its decline during the 1970-1980s. And vice versa, the recovery from eutrophication of the Black Sea ecosystem since the late 1990s (Kideys 2002) has improved the environmental conditions for scallops. *Rapana venosa* population has declined along the Bulgarian Black Sea coast due to trophic suppression and commercial harvesting (Janssen et al. 2014) and this relaxed the predatory pressure, thus creating an opportunity for bivalves to recover. *Flexopecten glaber* is known as a warm-water species of Mediterranean origin that hardly withstands low winter temperatures in the Black Sea (Nevesskaya 1965). Therefore, recent alterations of the Black Sea hydroclimate – "warmer winters over the last 14 years" before 2019 (Stanev et al. 2019) can clearly be associated with the observed scallop recovery and expansion.

Although *F. glaber* from the Black Sea displays significant decrease of genetic diversity compared to the Mediterranean populations (Slinko et al. 2020), wide morphological variability and phenotypic diversity is typical of the smooth scallop (Shcherban &Melnik 2020). Different shell colours have been demonstrated to be associated with varying somatic growth rate: the phenotypes with a high level of synthesis of protein structures were determined as off-white, purple and grey–brown (Shcherban & Melnik 2020). The predominance of off-white and brown scallops in the Bulgarian Black Sea population may have positive effect in potential scallop aquaculture.

Flexopecten glaber in the Bulgarian Black Sea attained similar maximum height (H = 53.48 mm) but smaller maximum weight (TW = 17.78 g) compared to Kazach'ya Bay (Crimea) population (53.4 mm and 23 g, respectively see Bondarev 2020). Small proportion of 5 % of the Kazach'ya Bay population attained MY=0.4, while the rest had similar meat yield of 0.2–0.3 as the Bulgarian population. The size and age structures of the two populations were clearly dissimilar: Kazach'ya Bay population was dominated by length classes 25–35 mm and age class 1 year, while the Bulgarian population was dominated by length classes 40–46 mm and age class of 4 years. These differences could have been caused by different harvesting selectivity but depth segregation of juveniles at smaller depth from adults at greater depth could also be presumed. Spatial migration of scallops is feasible due their capacity to swim actively by water jets from the mantle cavity, generated by shell adductions. Such natural phenomenon of depth segregation is known for *Donax trunculus* (see

Gaspar et al. 2002) but further research into depth distribution of *F. glaber* is required to reinforce that hypothesis.

The value of the growth constant (K=0.24) indicates that smooth scallops grow relatively slowly and attain their maximum size at rather advanced age. The asymptotic height H_∞ = 54 mm is close to the maximum measured height H = 53.48 mm of a presumably 9 year old specimen. Although that particular age reading could be over- or underestimated, it is certain that smooth scallops in the Black Sea reach at least 7 years of age as supported by our own data and by the age estimates of the population at the Crimean Peninsula (Bondarev 2019).

The smooth scallop potentially represents a valuable commercial resource for harvesting in the wild and for aquaculture. However, uncontrolled overfishing can lead to rapid stock depletion, as already seen in the Aegean Sea (Marčeta et al. 2016). Smooth scallops could also represent by-catch of *Rapana venosa* fishery. Due to relatively smaller size and weight of *F. glaber* in the Black Sea, its economic value could be lower. Nevertheless, commercial harvesting cannot be ruled out, if there is market demand. Therefore, it is critical to evaluate in advance the population distribution, abundance and dynamics in order to devise appropriate management measures before harvesting has started.

Aquaculture has advantages over commercial harvesting in the wild, being a more environmentally-friendly option that could ensure long-term sustainable profit. Growing number of investigations indicate *F. glaber* as a promising candidate to diversify shellfish culture production in the Adriatic Sea. The particular pros include health status unthreatened by serious pathogens, rapid growth and early maturation, good probability of catching spat by means of simple and inexpensive collectors (Marčeta et al. 2016; Prato et al. 2015), as well as beneficial nutritional and organoleptic properties (Berik et al. 2017, Prato et al. 2019). Although the environmental conditions in the Black Sea are characterised by lower winter temperatures and two-fold lower salinity than the Adriatic Sea, fully adapted and recently expanding *F. glaber* population is a prerequisite for positive perspectives for development of a new type of shellfish mariculture in the Bulgarian Black Sea waters.

Conclusions

Fflexopecten glaber has established substantial population in the Bulgarian Black Sea waters during the previous decade. The recovery followed the improved environmental and climatic conditions for the species. Commercial harvesting and by-catch represent an imminent threat that shall be precluded to protect a valuable resource from depletion. The smooth scallop is a promising candidate to diversify shellfish mariculture in the Bulgarian Black Sea.

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