*Journal of Shellfish Research*, Vol. 40, No. 1, 37–47, 2021.

# THE COLLAPSE OF A WEDGE CLAM FISHERY IN THE SPANISH MEDITERRANEAN COAST AND RECOVERY PROBLEMS

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***ABSTRACT*** In the sandy shores of the Spanish Mediterranean, *Donax trunculus* (Linnaeus, 1758) has a high commercial interest. In the Gulf of Valencia, poor management of fishing activity led to its closure in June 2015. The objective of this study was to analyze the evolution of the catches of *D. trunculus* before the closure of the fishery as well as the biomass and density of the population in the months following the closure, plus 2 y later. The area of study was located in the main fishing area of the Gulf of Valencia, which belongs to the fleet of the Gandia Fishermen's Guild. The fishing beds for this clam are found on sandy sediments in shallow waters (between 0 and 2 m). During the 10 y previous to the fishery closure, the annual catch per unit effort of *D. trunculus* suffered a sharp decrease, falling from values between 37 and 42 (kg small vessel$^{-1}$ d$^{-1}$) during the period 2004–2008 to 5.5 in 2014. After the closure, the biomass and density of the wedge clam showed a seasonal pattern, with maximum values in summer, as well as notable differences in densities along the shore in each sampled month. Furthermore, a different size–frequency distribution across depth, with smaller individuals in the shallower areas, was observed. Nevertheless, a general and considerable decline for biomass and density from 2015 (monthly mean of commercial biomass ranged from 24 to 48 kg ha$^{-1}$) to 2017 (from 4 to 13 kg ha$^{-1}$) was noted. This indicates that the closure did not improve the state of the population. There are several hypotheses that could explain this decline such as overfishing, changes in environmental conditions, higher predation (in benthic and planktonic phases), and the reduction of food availability. Therefore, there would be a need to study them in greater depth, as well as to increase the understanding of the spatial dynamics and connectivity of the *Donax* beds.

***KEY WORDS:*** clam, *Donax trunculus*, bivalve fishery, population structure, fishing gear selectivity

## INTRODUCTION

The surf-zone clams are found on sandy beaches throughout the world, with the most typical being the genus *Donax* (McLachlan & Defeo 2018). Within this genus, the wedge clam *Donax trunculus* (Linnaeus, 1758) is the species most characteristic of the sandy coasts of Europe (McLachlan et al. 1996, McLachlan & Defeo 2018). The filter feeder *D. trunculus* lives on sandy beaches in highly energetic environments because of its ability to bury itself in sediment (Ramón 1993, Gaspar et al. 1999b, McLachlan & Defeo 2018). On the Mediterranean coast, these organisms can be found up to 4 m deep, whereas they are preferentially distributed between 0 and 2 m deep (Ramón 1993, Ramón et al. 1995, Gaspar et al. 2002, Manca et al. 2002) and between 0 and 6 m on the Atlantic Coast (Gaspar et al. 2002). In general, juveniles are found in shallower areas, whereas adults are more abundant in deeper ones, both in Mediterranean Coast (Manca et al. 2002, Deval 2009, Baeta et al. 2018) and in Atlantic Coast (Ansell & Lagardère 1980, Gaspar et al. 2002). In some areas, such as the Atlantic Moroccan Coast, the inverse distribution has been observed by Bayed and Guillou (1985). This species shows a rapid increase in size and a short life span, lasting in the Spanish Mediterranean between 2–3 y (Ramón et al. 1995). The species *D. trunculus* has a high reproduction potential because of its small size at first maturity and spawning between tens of thousands to millions of oocytes (Ramón 1993, Tirado & Salas 1998, Louzán 2015, Delgado & Silva 2018).

The family Donacidae is under intense fishing pressure throughout the Southern Hemisphere, South Africa, South America, and Australia, as well as in Europe, with the wedge clam *Donax trunculus* being the most exploited species on Europe's sandy beaches (McLachlan et al. 1996, McLachlan & Defeo 2018). Despite the fact that the populations of these clams form aggregates with high density and can also be collected easily and economically (Castilla & Defeo 2001, Defeo & Castilla 2012), there is some difficulty in managing the fishery adequately. This is because, in addition to the factors directly and indirectly linked to fishing, these populations have naturally high variation in interannual densities (Defeo 1996, Delgado et al. 2017). In the case of *D. trunculus*, different natural factors can affect the survival and growth of this species, such as temperature (Neuberger-Cywiak et al. 1990, Manca et al. 2002), food availability (Ansell & Bodoy 1979), sediment grain size (Mazé & Laborda 1988, De la Huz et al. 2002, Lart et al. 2003, La Valle et al. 2011), parasites (Ramón et al. 1999, Ramadan & Ahmad 2010, de Montaudouin et al. 2014, Delgado & Silva 2018), and/or lethal or sublethal predation (Salas et al. 2001).

To establish adequate management measures, the biology and ecology of the species should also be considered (Gaspar et al. 2002). These measures could improve the selectivity and efficiency of fishing gears, and the protection of areas inhabited by juveniles (Gaspar et al. 2002). For some bivalves such as *Spisula solida* (Linnaeus, 1758) (Gaspar et al. 1999a, Gaspar et al. 2003), *Chamelea gallina* (Linnaeus, 1758) (Sala et al. 2014), *Venus striatula* (da Costa, 1778), and *Ensis siliqua* (Linnaeus, 1758) (Gaspar et al. 1999a), the selectivity of fishing gears has been analyzed. Few published accounts exist for *Donax trunculus*. In the Spanish Mediterranean and Portugal, Ramón (1993) and Lart et al. (2003) examined the selectivity of different fishing gears on *D. trunculus* based on the mesh size of the dredges. Ramón (1993) determined that the dredges with a metallic grid of 12-mm mesh size had adequate selectivity (the 50% retention lengths of 22.1 mm), whereas Lart et al. (2003), working with a semicircular iron structure with a net bag, established

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DOI: 10.2983/035.040.0105

a mesh size of 28 mm as the most suitable to obtain L50% close to 25 mm.

The fishery's closure during the reproductive and recruitment periods could be a strategy to avoid compromising the reproduction potential of *Donax trunculus*. Periods of closure for commercial exploitation, coinciding in general with the spawning season, have been carried out for *D. trunculus* in Spain (Catalonia and Andalusia) as well as in Portugal (Lart et al. 2003, Silva et al. 2014, Baeta et al. 2018, Andalusia Community Order of March 25, 2003, Andalusia Community Order of February 22, 2018). In Catalonia, after a decline in *D. trunculus* populations since the 1990s, biological closures along with a defined daily working schedule were established in 2002, allowing landings to recover by 2003 (Baeta et al. 2018).

The wedge clam has a high commercial interest in the sandy shores of the Spanish Mediterranean. In the last two decades, fishing in the Valencian region of Spain has been mostly limited to the fleet of the harbors of Cullera and Gandia. This fishery has never had appropriate management plans based on real data about the abundance and recruitment of *Donax trunculus*. The lack of adequate plans to control the fishing pressure likely contributed to a decline in catches over the last decade that led to the closure of the fishery in June 2015 (Valencian Community Resolution of June 3, 2015) until now. The objective of this research was to analyze the evolution of *D. trunculus* catches during the 10 y previous to the closure of the fishery as well as *D. trunculus* densities and biomass just before the closure of the fishery. In addition, the state of the population was analyzed during the 5 mo after the closure and a second time 2 y after. We hypothesize that because of the high reproductive potential of the species, the population will recover quickly after the closure.

## MATERIALS AND METHODS

The area of study is located in the sandy beaches in the southern sector of the Gulf of Valencia in the northwestern Mediterranean Sea, off the eastern coast of Spain. It encompasses all the beaches from Tavernes de la Valldigna until Denia, the *Donax trunculus* fishing ground of the fleet of the Gandia Fishermen's Guild (Fig. 1). These coasts are composed of sandy sea beds with a high proportion of fine sands, which increases with depth (Ramón 1993, Escrivá et al. 2020).

Data concerning the *Donax trunculus* fishery that covers the Gandia fleet fishing zones were provided by the Gandia Fishermen's Guild for the period 2004–2014. The annual evolution of *D. trunculus* fishery was analyzed based on data from annual catches in kilograms and the fishing effort (number of trips). On the basis of these data, the annual catch per unit effort (CPUE) was calculated (kg small vessel$^{-1}$ d$^{-1}$). In addition, total annual catch data for *D. trunculus* throughout the Spanish Mediterranean was provided by the Ministry of Agriculture and Fisheries, Food, and Environment of Spain for the period 2004–2014 (MAPAMA 2017).

To study densities and biomass of the wedge clam, two sampling programs were carried out: the first one in 2015 that included the month just before the fishery's closure and the five subsequent months. The second one was realized 2 y later in 2017, with a duration of 4 mo, and the closure still being in effect. Eleven sampling stations (Fig. 1; St1, …, St11) were located to cover heterogeneity of population, according to the areas previously determined by the regional fishery authority as production areas for bivalve molluscs in the Valencian Community waters (Valencian Community Resolution of February 19, 2013). Between May and November 2015, samples were obtained at two depths at each station, the first one from 0.5 to 1.5 m of depth (bathymetric range one or Stx_1) and the second one between 1.5 m and 3 m of depth (bathymetric range two or Stx_2). The first sampling was taken at each station between late May and early June 2015, before the closure of the fishery on June 10, 2015 (Valencian Community Resolution of June 3, 2015). Furthermore, immediately after the closure, monthly samplings were taken at stations 1, 4, 6, 8, 10, and 11, and bimonthly at stations 3, 5, 7, and 9 between July and November 2015. In 2017, between June and September, samples were taken monthly at the same five stations randomly selected (1, 3, 4, 7, and 8), but only in the bathymetric range 1.

The samples were collected using small vessels especially equipped with four dredges (70 cm wide each one) to catch *Donax trunculus*. Three of the four dredges had a metallic grid with a mesh size of 11.7 × 11.7 mm, which is standard for this fishery, and the fourth had a mesh size of 5 × 5 mm to catch individuals of different sizes of adults and juveniles. The shellfishing vessel cast a heavy anchor, called a ''potala,'' attached to a steel cable. It traveled to a predetermined distance and, after casting the four dredges, it wound up the cable with an auxiliary motor that managed to drag the small vessel and the dredges to the anchor point. The dragging was parallel to the coastline, and the distance was set at 100 m and verified with a GPS. Consequently, the swept area for each dredge was 70 m$^2$. The commercial size of this species was established in 2013 as 14 mm (Valencian Community Decree 94/2013), considering this value, in this study, as the minimum size of adults. Ramón (1993) determined the first maturation size of this clam to be 13 mm, and a similar size (15 mm) was used by Manca et al. (2002) to distinguish between juveniles and adults.

The anterior–posterior length of each clam caught in the 5-mm mesh size dredge was measured to the nearest 0.1 mm using a caliper. A total of 31,743 individuals were caught and measured. To obtain the relationship between biomass and length of the wedge clam, the anterior–posterior length of 193 individuals of all size classes was measured and weighed (precision ± 0.01 g). The parameters of this relationship were estimated by regression analysis:

$$W = aL^b, \tag{1}$$

where $W$ is the wet weight (g), $L$ the shell length (mm), $a$ is the intercept (initial growth coefficient), and $b$ is the slope (relative growth rate of the variables). The coefficient of determination ($r^2$) was used as an indicator of the quality of linear regression. The equation obtained was used to determine the weight of the rest of the individuals.

The total density (ind m$^{-2}$) of *Donax trunculus* was determined from the swept area for each sampling station in the 5-mm mesh size dredge. Furthermore, the density and the biomass (kg ha$^{-1}$) were calculated for commercial size individuals ($\geq$ 14 mm) in the same dredge. Changes over time of the population density and biomass were analyzed statistically by Kruskal–Wallis tests, and multiple comparisons of groups with the Bonferroni adjustment of $P$ values were implemented to assess statistically significant differences, due to nonnormal distributions of data. These tests were carried out using the software package Statgraphics Centurion XVII.

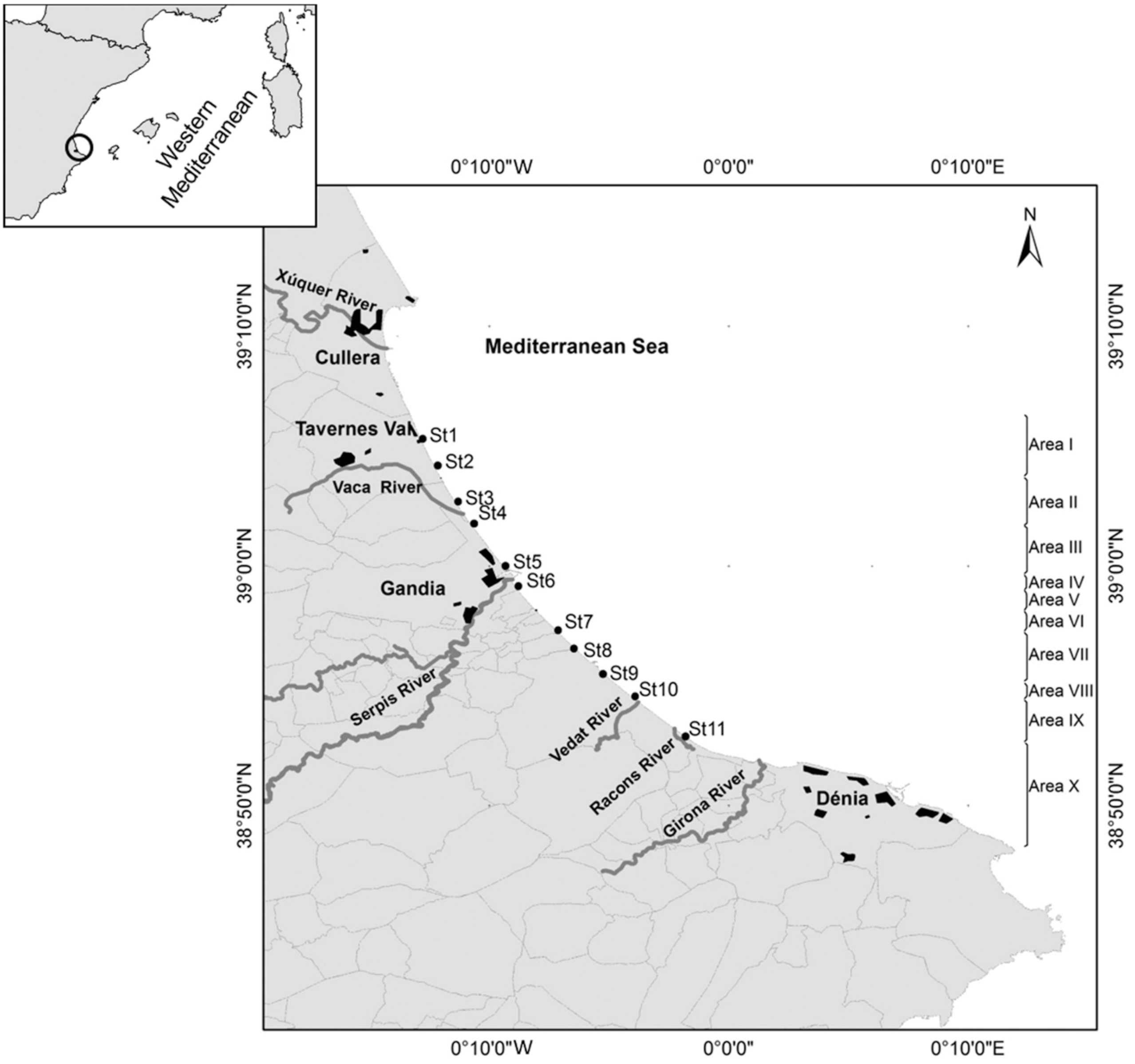

**Figure 1. Study area with sampling station.**

The length–frequency distribution was calculated for each month, separating individuals at intervals of 1 mm. The length–frequency distribution obtained was divided into cohorts applying the Bhattacharya's method using the FISAT II tool (Gayanilo et al. 2005) for 2015 and 2017 months, using only the data from the stations sampled monthly. Moreover, in the case of samples taken in 2015, differences between total and commercial density, and commercial biomass and length–frequency distributions among depths were analyzed. The Kolmogorov–Smirnov goodness-of-fit test (K-S) for two samples was applied, with a significance level of 95% ($\alpha = 0.05$).

In addition, organisms caught with the other three dredges of 11.7 mm in size were photographed *in situ* and returned to the sea. The individual sizes were obtained by means of digital analysis using the program ImageJ. The fishing gear selectivity was analyzed for all samples taken in 2015, through length–frequency distribution comparison between 5 and 11.7 mm mesh sizes dredges. Also, data on mesh size selectivity were analyzed and the parameters obtained using FISAT II (Gayanilo et al. 2005).

Monthly seawater temperatures for the area of study were obtained from NASA Goddard Space Flight Center (Ocean Biology Processing Group 2018), for the periods May to November 2015 and June to September 2017.

## RESULTS

### *Fishery Evolution During the Period 2004–2014*

The annual catches suffered an abrupt decrease during 2004–2014, falling from 100,000 kg y$^{-1}$ in 2004 to 1,600 kg y$^{-1}$ in

TABLE 1.

Annual catches, fishing effort, and the CPUE for *Donax trunculus* fishery in Gandia during the period 2004–2014.

| Year | Catches in Spanish Mediterranean Sea (kg) | Gandia Catches (kg) | Gandia Fishing effort (trips) | Gandia CPUE |
|---|---|---|---|---|
| 2004 | 228,350 | 101,627 | 2,611 | 38.9 |
| 2005 | 256,458 | 98,249 | 2,381 | 41.3 |
| 2006 | 200,454 | 90,664 | 2,137 | 42.4 |
| 2007 | 82,880 | 23,426 | 624 | 37.5 |
| 2008 | 152,358 | 62,912 | 1,694 | 37.1 |
| 2009 | 183,233 | 57,026 | 1,846 | 30.9 |
| 2010 | 145,623 | 30,976 | 1,645 | 18.8 |
| 2011 | 103,529 | 18,571 | 1,224 | 15.2 |
| 2012 | 98,549 | 12,273 | 807 | 15.2 |
| 2013 | 102,973 | 7,272 | 501 | 14.5 |
| 2014 | 104,195 | 1,597 | 291 | 5.5 |

CPUE, catch per unit effort. Annual catches of *D. trunculus* in the whole Spanish Mediterranean is also shown.

2014 (Table 1, Fig. 2). The downward trend was continuous over the years; however, in 2007, a particularly significant reduction was observed with respect to the general descent pattern. Nevertheless, the CPUE remained relatively constant, ranging between 37–42 during the period 2004–2008, including 2007, as both the catches and the fishing effort showed a notable decrease in that year. From 2009, an abrupt decline in the CPUE was observed, falling from 30.9 to 5.5 in 2014. In addition, the total annual catches of *Donax trunculus* in the whole Spanish Mediterranean are shown in Table 1. These values were between 200,000 and 250,000 kg $y^{-1}$ during 2004–2006. In 2007, there was a clear decline that increased again in the period 2008–2010 and remained stable, around 100,000 kg from 2011 to 2014.

### *Population Biomass and Density in 2015 and 2017*

The K-S statistical analysis of total and commercial density and commercial biomass did not reveal any significant differences between depths ($P = 0.3973$, $P = 0.5441$, $P = 0.7112$, respectively). Wide ranges in total density were observed for the months sampled in 2015 (Fig. 3A), with the widest values being in the month carried out before the fishery's closure. In 2017, the ranges were considerably narrower. In 2015, the mean and median values of total density increased after the closure of the fishery and remained high during July, August, and September. In 2017, the monthly means and medians of the total density were notably lower than those in in 2015, with a reduction in the medians of about 76%. The Kruskal–Wallis test and multiple comparisons of groups with the Bonferroni adjustment confirmed that the total density in the different months of 2017 was, in general, statistically lower than that in July, August, and September 2015 ($P < 0.0001$). A pattern similar to the total density was observed for commercial size individuals, but with narrower ranges (Fig. 3B). The means and medians of the commercial density, after the fishery's closure in 2015, were always above 2 ind $m^{-2}$, reaching the highest in July 2015 (4.45 and 4.28 ind $m^{-2}$ mean and median, respectively), whereas, in 2017, they did not exceed the value of 1 ind $m^{-2}$. The statistical analysis again indicated significantly lower values for the 2017 months.

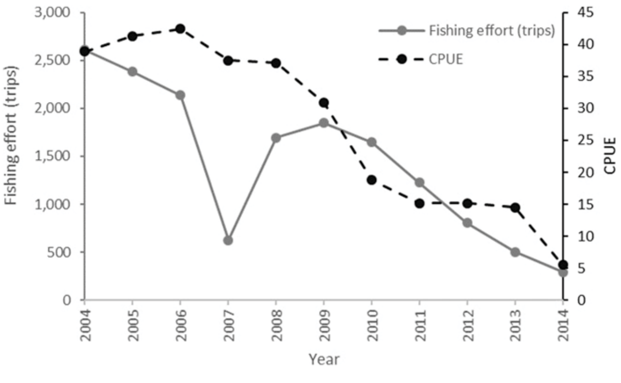

**Figure 2. Annual fishing effort and the CPUE for *Donax trunculus* fishery in Gandia during the period 2004–2014.**

The observed relationship between wet weight and length of *Donax trunculus* was $W = 9 \times 10^{-5}\ L^{3.1433}$, with $r^2 = 0.9782$ ($P < 0.0001$). The monthly biomass means and medians increased after the fishery's closure, although, subsequently, a decreasing trend was observed as the mean seawater temperature decreased (Table 2). In 2017, a biomass reduction in the medians of around 71% was observed. This decrease was even clearer when 2 mo with similar characteristics such as August 2015 and 2017 (both without fishery activity and with similar temperatures) were compared, noting that, in 2017, only one-sixth of the 2015 mean commercial biomass was found. The Kruskal–Wallis test and the *post hoc* Bonferroni indicated that biomass medians for August and September 2017 were significantly lower than those observed in July and August 2015 ($P < 0.0001$).

As regards the spatial distribution of the commercial biomass, the maximum values were obtained more frequently at St4 (approximately 45, 15, 16, and 8 kg $ha^{-1}$ in November_15, June_17, July_17, and September_17, respectively), although St1, St3, and St7 presented even higher maximum values in some months in 2015 (Table 2). It is interesting to note that St4 was clearly the most frequent station where the highest values were observed in 2017, especially when St1, St3, and St7 stations were among those sampled in this second sampling program. The lowest values were more regularly obtained at St5 in 2015 and at St8 in 2017.

### *Length–Frequency Distribution*

Bhattacharya's method allowed, in general, the separation of three cohorts with the exception of June 2017 (Fig. 4). Before the closure, three cohorts were found. The mean length and standard deviation of the first cohort was 8.39 ± 1.82 mm ($n = 299$), the second 12.78 ± 1.38 ($n = 418$), and the third 21.15 ± 2.4 mm ($n = 565$). The mean size of the three cohorts increased until October 2015, when the mean sizes of the three cohorts were the highest (with 14.27 ± 2.48 mm, 18.83 ± 1.86 mm, and 23.77 ± 1.9; $n = 890$, 401, and 102, respectively). In November 2015, the mean size of the cohorts decreased. A similar pattern was observed for 2017.

Of all samples taken in 2015, the highest proportion of individuals was between 14 and 18 mm, being between 11 and 17 mm in bathymetry 1 and 14 and 18 mm in bathymetry 2. The

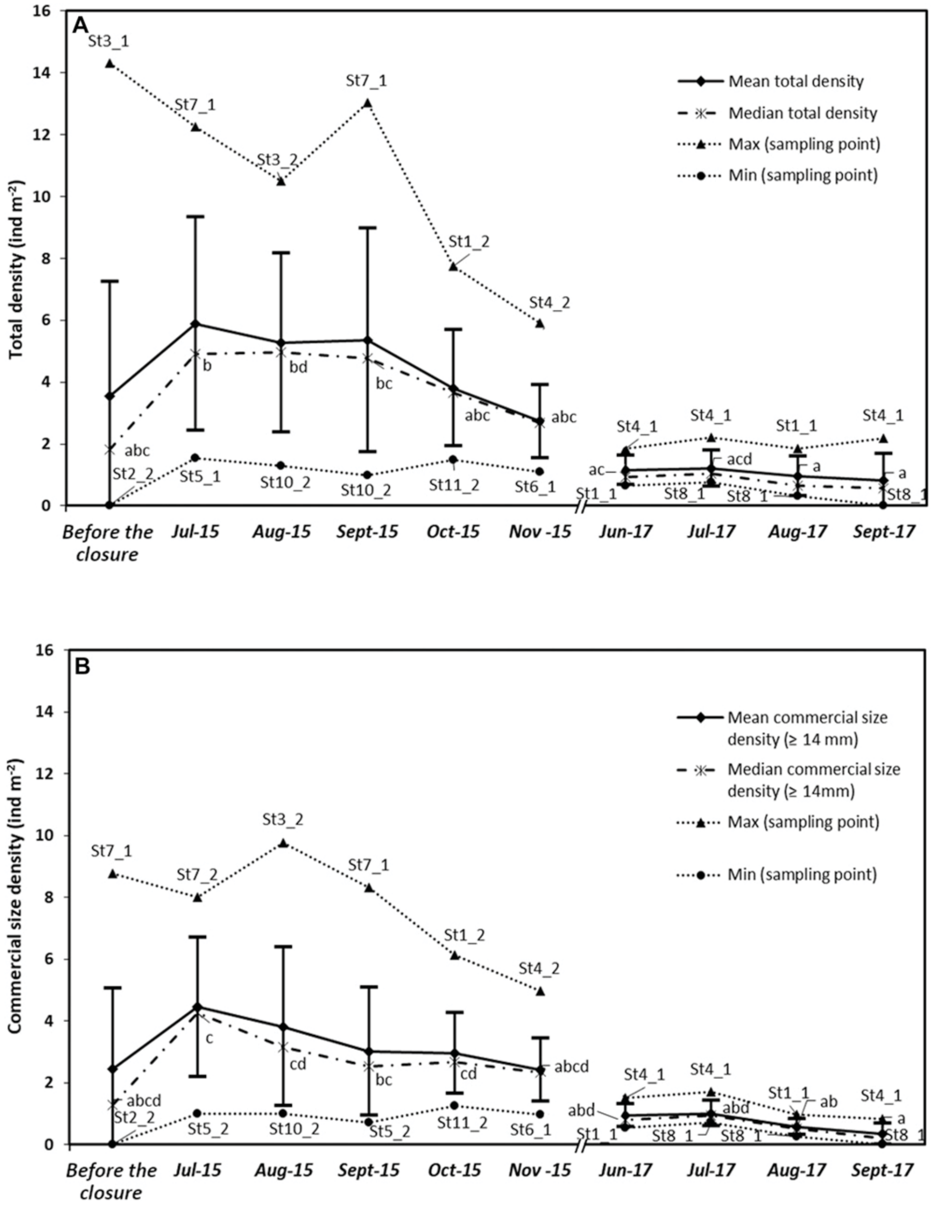

**Figure 3. (A) Total density. (B) Commercial size density (≥14 mm) of *Donax trunculus* in the 5-mm mesh size dredge. Medians, means, and SD; maximum and minimum values; and the stations where they were obtained are shown. The letters following medians indicate the Kruskal–Wallis test and multiple comparison of groups with Bonferroni adjustment (the months that do not share the same letter are significantly different).**

K-S test revealed the existence of significant statistical differences in the length–frequency distributions between depths in the 2015 sampling ($P < 0.05$), where the appearance of smaller individuals was more frequent in the shallowest areas (Fig. 5). In 2017, the wedge clam length–frequency distribution showed the highest proportion of individuals (55.4%) to be between 14 and 23 mm.

### *Selectivity*

Across all samples, the size of virtually 100% of individuals caught in the 11.7 mm mesh size dredge was bigger than the minimum value established by legislation (14 mm). When individuals were noted to be smaller than the minimum size, these organisms did not exceed 1% of the total sample of *Donax trunculus* in bathymetry 1 and 1.3% in bathymetry 2. In the case of the larger mesh size dredge, the individuals between 21 and 25 mm appeared more frequently. The 5-mm mesh size dredges showed the existence of juveniles in the population from 5 mm in length; however, one case was noted when an individual was smaller (4.4 mm at St4_1 in October). The juveniles (< 14 mm) represented a percentage between 5% and 70% of the organisms caught in the 5-mm mesh in bathymetry 1; meanwhile, a lower percentage, between 0% and 57%, was observed in the deeper area.

The 25% retention length was 24.69 mm, whereas L50% was 25.25 mm, and L75% showed a value close (25.81 mm) (Fig. 6).

TABLE 2.

**Monthly mean and median of *Donax trunculus* commercial size (≥14 mm) biomass in the 5-mm mesh size dredge.**

| Fishery's closure | Month (Temperature) | Mean (kg ha$^{-1}$) | SD | Median (kg ha$^{-1}$) | Minimum (kg ha$^{-1}$) | Minimum (St) | Maximum (kg ha$^{-1}$) | Maximum (St) | % Samples ≥20 kg ha$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| Before | May–June-15 (21.7°C) | 30.26 | 29.21 | 17.94*†‡§ | 0.00 | St2_2 | 108.05 | St3_1 | 45.5 |
| After | July-15 (26.4°C) | 48.08 | 22.13 | 48.10§ | 12.59 | St5_2 | 79.58 | St7_2 | 85.7 |
| | August-15 (26.8°C) | 38.18 | 25.49 | 30.35‡§ | 11.75 | St10_2 | 100.66 | St3_2 | 75.0 |
| | September-15 (24.9°C) | 27.80 | 19.65 | 24.00*†‡§ | 7.20 | St5_2 | 75.26 | St7_1 | 56.3 |
| | October-15 (22.3°C) | 27.04 | 12.58 | 25.06†‡§ | 7.21 | St11_2 | 51.56 | St1_2 | 75.0 |
| | November –15 (19.3°C) | 24.28 | 10.41 | 23.78*†‡§ | 10.46 | St5_1 | 45.13 | St4_2 | 66.7 |
| | June-17 (24.5°C) | 10.63 | 3.07 | 10.28*†‡ | 7.05 | St1_1 | 14.91 | St4_1 | 0.0 |
| | July-17 (25.5°C) | 12.46 | 2.82 | 13.03*†‡§ | 9.58 | St3_1 | 16.18 | St4_1 | 0.0 |
| | August-17 (26.8°C) | 6.56 | 2.63 | 6.60*† | 2.94 | St8_1 | 9.07 | St1_1 | 0.0 |
| | September-17 (25.2°C) | 3.52 | 3.39 | 2.20* | 0.17 | St8_1 | 7.74 | St4_1 | 0.0 |

SD, minimum and maximum values with the station where they were obtained, and the percentage of samples that reached or exceeded 20 kg ha$^{-1}$ in each month are presented. The monthly seawater surface temperature is also shown in brackets. The symbols following medians (*, †, ‡, §) indicate the Kruskal–Wallis test and multiple comparison of groups with Bonferroni adjustment (the months that do not share the same symbol are significantly different ($P < 0.05$)).

## DISCUSSION

### *Ecological Aspects of* Donax trunculus *Populations*

The study zone presented a different size–frequency distribution across depth, with the highest frequency of smaller organisms in shallower areas (Fig. 5). The most frequently obtained sizes in 2017 were somewhat bigger than in bathymetric range one of 2015 and even similar to the sizes from the deeper zone of 2015. A similar pattern was also found in several other studies carried out along the Catalan Coast of Spain (Baeta et al. 2018), Portugal (Gaspar et al. 2002), the French Atlantic coast (Ansell & Lagardère 1980), Italy (Manca et al. 2002), and Turkey (Deval 2009). Each study found a prevalence of smaller individuals in shallower waters, whereas larger ones occurred mainly in the deeper bathymetric ranges. Gaspar et al. (2002) explained the distinction in depth as a survival strategy, in which the juveniles once grown migrate toward deeper areas, giving more space for the settlement of larvae in shallower areas. Moreover, the establishment of juveniles in shallower areas could be due to a higher availability of food and a greater tolerance to decreases in salinity in these areas (Scheltema 1971, Reyes-Martínez et al. 2020). The shallower areas can function as a source of *Donax trunculus* due to currents and hydrodynamism passively pushing the larvae into this zone, facilitating colonization (Manca et al. 2002).

Through the analysis of the evolution of cohorts, an increase in the mean size was observed during 2015, which confirmed that the populations thrived with time and increased in size each month, showing the same pattern in 2017. According to Ramón (1993), the reproduction period of *Donax trunculus* in an area close to the study zone begins in June, with recruitment between July and September (Ramón 1993, Ramón et al. 1995). In November 2015, a new first cohort with a smaller mean size was observed, which could be due to the fact that recruited individuals in the previous months could have already exceeded 5 mm and consequently have been caught.

### *Fishing Aspects of* Donax trunculus

According to fishermen, a minimum of 20 kg per working day per small vessel should be obtained to be profitable (E. Ferrer, personal communication, Gandia Fishermen's Guild 2015). From 2010, it was observed that the CPUE dropped to values less than 19, and yet despite this, the fishery still continued for another 4 y (Fig. 2). This would indicate that one way or another it was profitable to continue with the exploitation of this species, leading to the suspicion that part of the catches may not have been declared, as observed by Baeta et al. (2018) in another area of Spain, where up to 20% of catches were sold through unofficial channels. Just before the fishery closure, the minimum profitable level of 20 kg ha$^{-1}$ for the biomass was reached or exceeded in only 45% of the cases, thus the fishing had a low profitability (Table 2).

With respect to the selectivity parameters obtained using FISAT II (Fig. 6), the L25, L50, and L75 values (24.69, 25.25, and 25.81 mm, respectively) were higher than the minimum size landing (14 mm) established by legislation and higher than the first maturation size of 12.7 mm (Ramón 1993); therefore, the fishing gear could be considered to have an appropriate selectivity. In a previous selectivity study carried out in the Gulf of Valencia, lower 25%, 50% and 75% retention lengths (19.7, 22.1, and 24.5 mm, respectively) for *Donax trunculus* were noted (Ramón 1993). From then on, it was agreed that no modification of the mesh size was necessary (Ramón 1993). A minimum landing size of 25 mm was set in other areas of Spain (Gulf of Cadiz and Catalonia) and other countries such as Portugal (Lart et al. 2003, Silva et al. 2014, GENCAT 2015, Andalusia

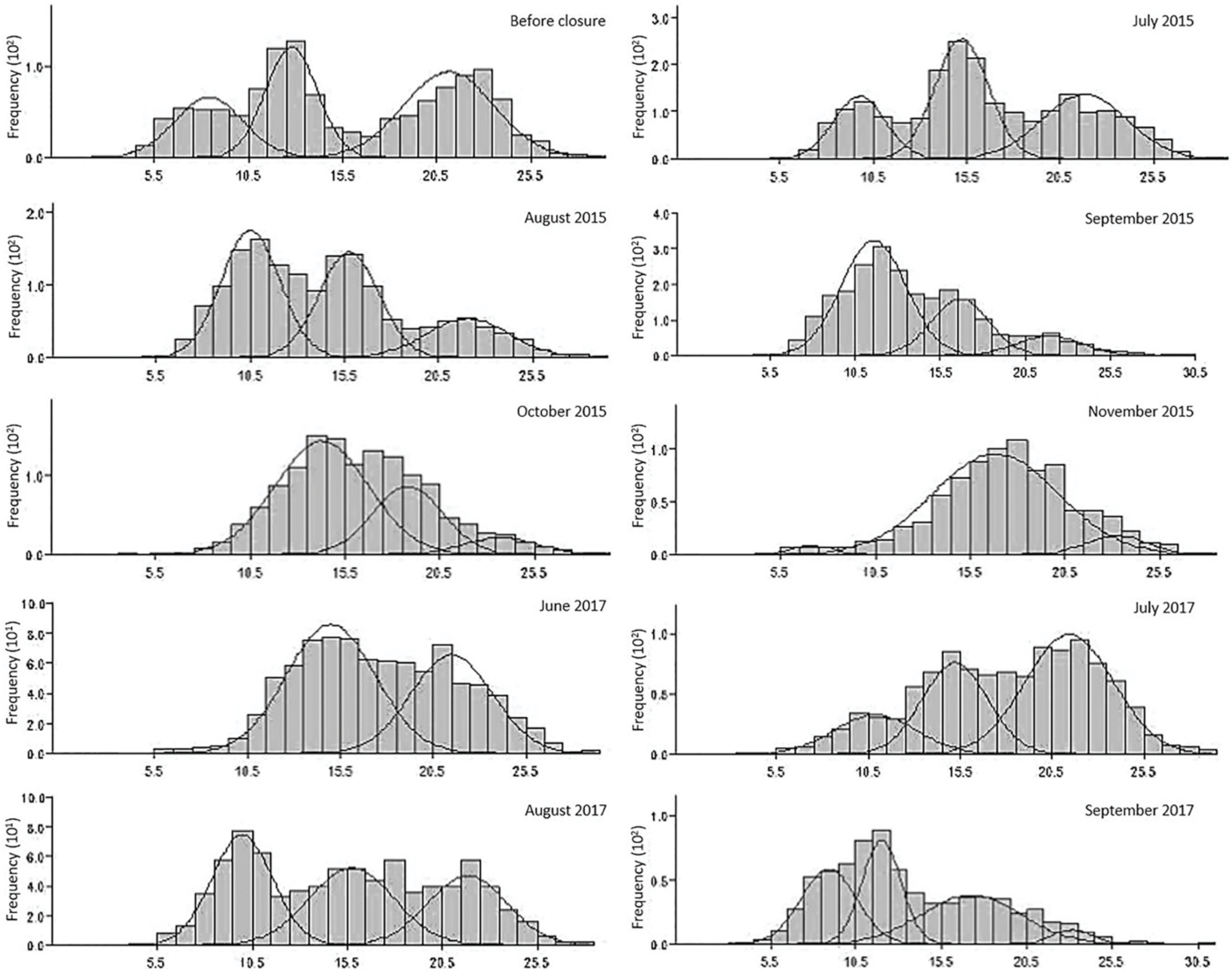

Figure 4. Monthly length–frequency distribution of *Donax trunculus* for the 5-mm mesh size dredge. Curves represent the cohorts.

Community Order of February 22, 2018). Nevertheless, although the fishing gear analyzed in the current study showed an adequate selectivity, it would be advisable to establish a larger commercial size of 25 mm, to benefit the sustainability of exploited beds. A minimum landing size of 14 mm, a size very close to the size at first maturation, could affect the survival of the species due to the individual not growing large enough to maximize its reproductive potential because oocyte production is positively related to size (Delgado & Silva 2018).

Lart et al. (2003), among other authors, proposed that to conserve the growth of the stock of an exploitable population, it could be possible to implement closures of the fishery during the reproductive and recruitment periods, for periods of several years and/or rotational closures as management tools. Notwithstanding, in our case, the growth of the stock 2 y after the fishery closure was not observed (Table 2, Fig. 3). Other bivalve fisheries which were closed to encourage population recovery have been studied in the Mediterranean and Atlantic. Baeta et al. (2018) carried out an analysis of the bivalve fishery of *Callista chione* (Linnaeus, 1758) in NW Mediterranean, where the fishing activity was suspended for a year to recover the population. At the end of the suspension, a recovery was not observed; therefore, many fishermen decided to abandon the fishery of this clam, leaving residual activity until the permanent closure 6 y later. By contrast, in Uruguay (Atlantic), the fishery of *Mesodesma mactroides* (Reeve, 1854) showed an immediate recovery after a 1-y suspension (Defeo 1996, Brazeiro & Defeo 1999, Ortega et al. 2012). Nevertheless, when the suspension lasted more than 3 y, the increase in population was accompanied by a notable decrease in recruitment; thus, such a long period of closure may cause negative consequences (Defeo 1996, Brazeiro & Defeo 1999). Therefore, it is worth noting that, as observed here, fishery closures are not always effective in increasing commercial biomass, as other variables (e.g., pathologies, pollution, climate change, and higher rates of predation) could affect populations, leading them to levels close to extinction (Baeta et al. 2018).

### *Catches and Population Evolution*

It should be noted how important the Gandia fishery was when compared with the catches made along all Spanish Mediterranean Coast during 2004–2014 (Table 1). Between 2004 and 2008, *Donax trunculus* catches from Gandia represented around 40% of the total catches in the Spanish

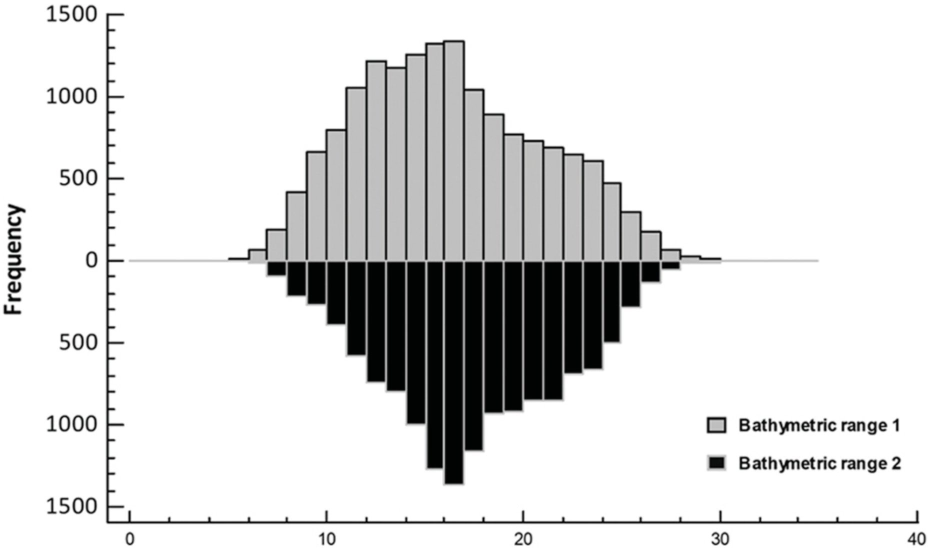

**Figure 5. Length–frequency distribution of *Donax trunculus* for the two bathymetric ranges sampled in 2015 in the 5-mm mesh size dredge. Bathymetric range 1: from 0.5 to 1.5 m and bathymetric range two between 1.5 and 3 m of depth.**

Mediterranean, except in 2007 when they dropped to 30%. From 2009, a clear downward trend began with 30% for that year, reaching 2% in 2014. The trends in catches in Gandia and the rest of the Spanish Mediterranean were different, showing a very sharp decrease in the study area. The CPUE is considered as an index of relative abundance (Gatica & Hernández 2003) and gives us information about the state of species exploitation. The marked decrease in the CPUE values from 2009 to 2014 could indicate that the fishery had suffered from overexploitation, although the lack of recovery of the populations, once the fishery was closed, led us to consider alternative hypotheses. Declines in catches of *D. trunculus* were observed in the Mediterranean coasts of Lazio, where changes in sediment granulometry were considered the most likely cause (Lart et al. 2003). Baeta et al. (2018), in the Catalan Coast, observed a marked drop in *D. trunculus* landings between 2007 and 2015 as a consequence of high fishing pressure, inadequate management, plus undetermined factors.

The biomass values showed notable differences along the shore both before and after the closure (Table 2). Natural spatial variations are common in the sandy beach populations, tending to have aggregations in patches along the shore (McLachlan & Defeo 2018). Nonetheless, when populations are subjected to commercial exploitation, it is difficult to separate between the natural variations in abundance and the effect that commercial fishing has on them (Castrejón & Defeo 2015). Despite this, it is evident that the magnitude, extent, periodicity, and intensity of fishing pressure affect their distribution and abundance.

In 2015, a rapid increase in density and biomass was observed in the area of study after the fishery closure (July–August–September 2015) (Table 2, Fig. 3). Nevertheless, subsequently, a downward trend was observed as the mean seawater temperature decreased. Regarding the samples taken in 2017 from June to September, a relatively similar trend was observed, with the highest value found in July. The postclosure increase in 2015 was likely due not only to the lack of fishing activity but also to higher temperatures which cause an increase in physiological processes such as alimentation (Dionicio & Flores 2015) and reproduction (Ansell & Lagardère 1980, Manca et al. 2002), which could make individuals stay closer to the sediment surface. Later, when the temperature decreases (October and November), larger organisms tend to bury themselves deeper (McLachlan & Defeo 2018), causing a decrease in density and biomass of both total and commercial sizes. Manca et al. (2002), in a study carried out on the South Adriatic Coast, also detected a decline in the densities of *Donax trunculus* during autumn–winter (between November and January), in which a decrease in water temperature was a determining factor in the population density variations.

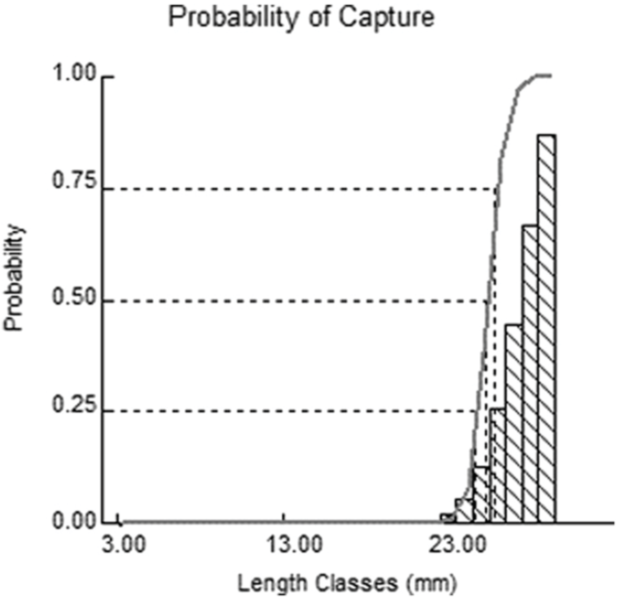

**Figure 6. Trawl-type selection curve for *Donax trunculus* fishing gear in Gandia, and retention lengths (L25%, L50%, and L75%).**

A general and considerable decline in biomass and density in 2017 could be seen compared with the 2015 values. Despite the high reproductive capacity of this bivalve, a recovery did not occur, which leads us to consider alternative hypotheses about the possible causes of this: (1) a reduction in the number of breeders which would affect population structure and recruitment (Delgado & Silva 2018), as well as ineffective connectivity between populations (Nantón et al. 2017, Fernández-Pérez et al. 2018) as a consequence of the overexploitation of the species; (2) changes in environmental conditions. Shrinidhi et al. (2018) observed mortality events for *Donax incarnatus* (Gmelin, 1791) due to changes in temperature and salinity. Thippeswamy and Joseph (1991) suggested that the beach grain size was also involved in the mortality of donacid bivalves; (3) top-down control. Parasitic interactions and predation (both in the benthic and planktonic phases) generate significant mortality and/or castration of Donacidae (Schneider 1982, Ramón et al. 1999, Salas et al. 2001, Pérez-Ruzafa et al. 2002, Ramadan & Ahmad 2010, de Montaudouin et al. 2014, Delgado & Silva 2018, Garcia et al. 2018); and (4) bottom-up control. Food availability and composition may also influence the abundance of Donacidae (Defeo & de Alava 1995).

Nantón et al. (2017) and Fernández-Pérez et al. (2018) studied the genetic diversity to understand the connectivity between the different *Donax trunculus* fishing grounds along the Spanish coasts, which is essential information for conservation and stock management policies. They identified three genetically differentiated zones: Atlantic Ocean, Alboran Sea, and the northwestern Mediterranean Sea. The study zone presents a high long-term risk of the extinction of the populations (Marie et al. 2016). To test the hypothesis 1, it would be therefore needed to figure out the structure of the metapopulation at greater depth and to find out the larval dispersion to establish the connectivity between populations and their resilience to overexploitation. Based on the hypothesis 2, the temperature is ruled out because of the fact that there were no significant differences in the mean seawater temperature between the periods of 2015 and 2017. Salinity has also been excluded owing to the fact that *D. trunculus* is capable of supporting long periods of low salinity, between 19.2 and 36.7 (Reyes-Martínez et al. 2020), and lower values are rarely found in the study area due to the Mediterranean regime of the rivers of the area (dry period during the summer and a wet period mainly in autumn) and the artificial regulation and intensive water use, leading to a situation of nonpermanent flow in their final sections (Sospedra et al. 2018). The change in the sediment grain size is not considered either because the study area had an adequate granulometry for the distribution and abundance of *D. trunculus* (Escrivá 2019). The top-down control could be produced by Scyphozoa in the planktonic community (Purcell 1992, Mills 1995, Pérez-Ruzafa et al. 2002), affecting the recruitment of *D. trunculus*. In the study zone, Scyphozoa such as *Rhizostoma pulmo* (Macri, 1778) and *Cotylorhiza tuberculata* (Macri, 1778) have presented blooms between 2010 and 2017 (GVA 2017). It is also worth mentioning the uncertain repercussions that the arrival of invasive alien species could have on the clams. From 2014–2015, numerous individuals of the blue crab *Callinectes sapidus* (Rathbun, 1896) have been detected in the Gulf of Valencia (Mancinelli et al. 2017). Although *C. sapidus* feeds a great variety of organisms, the bivalves are an important source of food, accounting for up to 50% of the blue crab's diet (Seitz et al. 2003). It is for this reason that the *D. trunculus* populations could have been affected by the increasingly abundant crab. Parasitism, benthic predation, and predation of larvae in their planktonic phase would need to be investigated in greater depth to determine to what extent they may be affecting the population density of this species. Regarding the last hypothesis, changes in nutrient flux, such as those of silica, could limit diatom growth, which predominate in turbulent sublittoral zones (McLachlan & Defeo 2018). In the study zone, Sospedra et al. (2018) established that more than half of the silica present in the coastal zone comes from the input of groundwater. Nevertheless, the availability of silica may have changed due to the decline of coastal wetlands because of changes in land use (Sebastiá-Frasquet et al. 2014).

## CONCLUSIONS

A sharp decline in commercial populations of *Donax trunculus* (2004–2014) led to a closure of the fishery in 2015. Several hypotheses could explain this decline, including overfishing, changes in environmental conditions, higher predation in both the benthic and planktonic phases, and the reduction of food availability. Although spatial and temporal variability in density showed ecological patterns consistent with the literature, populations did not recover 2 y after the fishery was closed. It is likely that a critical threshold would have been reached at which ecological resilience declined, and various environmental disturbances could have had a more noticeable impact. This poses the need for further studies regarding abiotic and biotic factors, which could be affecting the abundance or survival of these bivalves, as well as a greater understanding of the spatial dynamics and connectivity of the *Donax* beds.

If the fishery is to recommence, new management tools, such as increasing minimum catch size, and establishing fishing closures to coincide with reproduction and recruitment seasons, should be examined.

## ACKNOWLEDGMENTS

We would like to thank the Gandia Fishermen's Guild for their collaboration and the fishermen who helped in biological sampling. We would also like to thank the anonymous reviewer for the comments and suggestions that improved the manuscript.

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