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# Fishery dynamics of blue whiting, *Micromesistius poutassou*, a highly discarded bycatch species in the NW Mediterranean Sea

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**Summary:** This study characterized the fishery dynamics of blue whiting, a bycatch species of the bottom trawl Norway lobster fishery, in the NW Mediterranean. Landings and effort data over the last two decades were combined with current information on the spatial distribution of effort and catch, and with the size and age structure of blue whiting over the year. Recruitment to the demersal habitat occurred from 5 cm total length (TL) over the shelf break in spring (April-May), when discards showed the highest values (>95% of the catch). Adults were located over the upper slope, and large individuals (≥26 cm TL) were abundant during the reproductive period (January-March). A decline in landings has been observed in the last decade, probably related to the absence of intense deep convection processes in winter since 2013, which favour recruitment of the species. The effect of exploitation on the decrease in landings cannot be disregarded considering that the bulk of the catch is made up of immature (age 0) individuals, and the presence of old individuals is very low.

**Keywords:** discards; recruitment; population dynamics; landings; age structure.

**Dinámica de la pesquería de la bacaladilla, *Micromesistius poutassou*, una especie acompañante altamente descartada en el Mediterráneo noroccidental**

**Resumen:** Para un enfoque ecosistémico en la gestión de las pesquerías, se requiere información actualizada sobre el estado de explotación de las especies acompañantes. El presente estudio caracteriza la dinámica de la pesquería de la bacaladilla en el Mediterráneo noroccidental, una especie acompañante de la pesquería de arrastre de la cigala. Los datos sobre la captura desembarcada y el esfuerzo pesquero de las últimas dos décadas se combinaron con información actual sobre la distribución espacial del esfuerzo pesquero y de la captura, y con la estructura de tallas y edades de la población de bacaladilla a lo largo del año El reclutamiento al hábitat demersal tuvo lugar a partir de los 5 cm TL en el margen de la plataforma continental en primavera (abril-mayo), cuando se detectaron los mayores valores de captura descartada (>95% de la captura). Los adultos se localizaron en el talud-superior y los individuos más grandes (>26 cm TL) fueron abundantes durante el periodo reproductivo (enero–marzo). Se observó un descenso en las capturas durante la última década, probablemente relacionada con la ausencia de episodios intensos de convección profunda en invierno desde el 2013, que favorecen el reclutamiento de la especie. Sin embargo, no se puede obviar el efecto de la explotación ya que la mayor parte de la captura se basa en individuos inmaduros (edad 0).

**Palabras clave:** descartes; reclutamiento; dinámica poblacional; captura desembarcada; estructura de edades.

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## INTRODUCTION

Mediterranean bottom trawl fisheries are typically multi-species, that is, they are characterized by a large variety of species and the absence of large single-species stocks. Three groups of vessels operate in these fisheries: coastal trawlers, which target a wide variety of species (e.g. red mullet, common squid, curled octopus, European hake and monkfish); trawlers operating on the shelf break and upper slope, with Norway lobster as the main target species; and trawlers operating in submarine canyons, with blue and red shrimp as the target species (Martín et al. 2014). Mediterranean fisheries are characterized by marked seasonality in landing composition and the presence of very young individuals (Lleonart and Maynou 2003). Bottom trawl discards, including species with and without commercial value, have been estimated to be around 30% of the total catch (Sánchez et al. 2004; Tsagarakis et al. 2014).

The exploitation of many demersal stocks in the western Mediterranean Sea far exceeds the levels required to achieve the maximum sustainable yield (MSY) (Colloca et al. 2017). At present, a multi-year plan for demersal fisheries (2019-2025) is being implemented in the western Mediterranean (EU 2019a) with the aim of reaching and maintaining the MSY for the target stocks. On the Catalan coast (northern part of the General Fisheries Commission for the Mediterranean (GFCM-FAO) geographical subarea GSA 6), these are Norway lobster (*Nephrops norvegicus*), blue and red shrimp (*Aristeus antennatus*), deep-water rose shrimp (*Parapenaeus longirostris*), European hake (*Merluccius merluccius*) and red mullet *(Mullus barbatus*). The plan should also adopt the ecosystem-based approach to fisheries management in order to minimize negative impacts of fishing activities on the marine ecosystem, i.e. it should also take into account bycatch species caught in demersal fisheries and stocks, which play an important role in the ecosystem functioning but insufficient data are available on them.

Blue whiting (*Micromesistius poutassou*) is an oceanic, semi-pelagic species that is widely distributed in the NE Atlantic and in the Mediterranean Sea over the shelf break and upper slope (Bailey 1982, Farriols et al. 2019). It plays an important role in the marine food webs, feeding on pelagic crustaceans and Myctophidae fish (Bachiller et al. 2016, Mir-Arguimbau et al. 2020a) and being consumed by a wide range of predators, such as fish, sharks and flying squids (e.g. Cabral and Murtra 2002, Bailey 1982). In the NE Atlantic, large scale migrations of the species linked to reproduction and feeding grounds have been reported (Bailey 1982, Hátún et al. 2007), but within the Mediterranean such migrations have not been described (Martín et al. 2016). In the Atlantic, the spawning period starts in January-February in its southern distribution area, extending northwards with a time lag in relation to the latitudinal temperature gradient (Bailey 1982). In the Mediterranean, the species reproduces in winter, from December to March (Serrat et al. 2019, Mir-Arguimbau et al. 2020b), when temperatures reach the minimum values (12°C–13°C) (Calvo et al. 2011).

In the Atlantic, blue whiting distribution in the water column extends between 200 and 600 m depth. At less than 500 m bottom depth the species is found associated with the seabed, while in deeper waters (bottom depth >500 m) the species is located in the water column, at around 400 to 500 m (Johsen and Godø 2007). Blue whiting performs dial vertical migrations and is generally distributed deeper and more concentrated during daylight (Cohen 1990, Johsen and Godø 2007). These characteristics allow the species to be exploited in different ways, by pelagic trawl in the Atlantic and bottom trawl in the Mediterranean. Information on the blue whiting fisheries in the NE Atlantic dates back to 1977 (Hátún et al. 2007). There, the highest biomass is found along the edge of the continental shelf in areas west of the British Isles and on the Rockall Bank plateau, where blue whiting occurs in large schools at depths ranging between 300 and 600 m (ICES 2020). Over the period 1981-2020 landings displayed marked variations. Landings remained at around 0.5 million t until the mid-1990s, then steadily increased and exceeded 2 million t in 2003 and 2004. After a sharp decrease and very low landings in 2011, landings started rising again, and current landings (2020) are around 1.5 million t (ICES 2007, 2020).

In the Mediterranean, blue whiting is not a bottom trawl target species but a bycatch of the Norway lobster fishery, and it does not generate high income (Martín et al. 2014). Most bycatch species are unregulated and are not assessed (Mytilineou et al. 2021). No minimum conservation reference size has been defined for blue whiting (EU 2019b) although on the Spanish Mediterranean coast a minimum landing size has been established at 15 cm total length (TL) (BOE 2006). In 2010 a change of the mesh size was implemented, from 40 mm diamond to 40 mm square mesh size (EC 2006). Landings are far lower than in the Atlantic. Over a thirty-year period, from 1970 to 2000, annual landings fluctuated and remained above 8000 to 10000 t, with the highest values around 14000 to 16000 t. Since the mid-2000s landings have displayed a decreasing trend and are now at the lowest values of the whole time series, at around 2000 t, although a slight increase in landings has been observed in the most recent years (http://www.fao.org/fishery/statistics/global-capture-production/en). In the northwestern basin, blue whiting has been traditionally exploited. Landings records on the Catalan coast (around 580 km) are available since the early 1940s (Bas 1963). Over two decades, the 1940s and 1950s, landings ranged between 1300 and 3500 t; minimum landings were observed at the beginning of the time series in 1942 (*ca*. 700 t). In the most recent years, since 2012, landings have remained at very low levels, around 500 t or lower (Generalitat de Catalunya 2021a).

Most of the Mediterranean fisheries are based on the youngest ages (0 and 1) (Lleonart and Maynou 2003). According to the most recent stock assessments (STECF 2014), in the western Mediterranean (GSA 6) blue whiting exploitation was based on age classes 1 (dominant in the catch) and age 2, while in the Ligurian and northern Tyrrhenian Seas most of the caught specimens ranged between ages 1 and 3. Discards were

reported to amount to 15% of the catch in weight in the Ligurian and less than 5% in the northern Tyrrhenian. The conclusion of the assessment in both areas was that blue whiting was exploited unsustainably.

The present study aimed to characterize the fishery dynamics of blue whiting in the NW Mediterranean, i.e. discards, landings trend and seasonality, exploited sizes and age structure, and recruitment timing. From this fisheries-dependent information, biological traits of the species will be identified, such as spatial distribution by size and age over the year and the recruitment size to the demersal habitat. To this end, we combined landings and effort data over the last two decades with current information on the spatial distribution of fishing effort, catch, size and age structure of blue whiting over the year. The study will ultimately shed light on the status of blue whiting, a bycatch species, providing valuable information that is required in the ecosystem approach to fisheries management.

## MATERIALS AND METHODS

On the Catalan coast (NW Mediterranean), blue whiting is caught exclusively with bottom trawl during daylight hours as a bycatch from the vessels targeting Norway lobster (Martín et al. 2014, Ordines 2014). The fishing vessels operate five days a week, with a maximum of 12 hours at sea. Landings are commercialized daily at the auction upon the arrival of the trawlers at the port. At present, the bottom trawl fleet on the Catalan coast consists of 221 vessels, 21 of them based in Roses fishing port (Generalitat de Catalunya 2021b, Roses Fishers Association 2021).

Data on blue whiting landings (daily and monthly) and effort (fishing days with reported blue whiting landings) on the coast of Catalonia and in Roses harbour over the period 2000-2020 were taken from the statistics of the Fisheries Service of the Generalitat de Catalunya. In 2012-2014 a blue whiting daily quota was implemented by internal agreement among fishers (i.e. no legal obligation) by establishing a maximum number of boxes depending on the size of the vessel. The fishing days with blue whiting landings were taken as representative of the fishing effort applied to the species because only a part of the trawl fleet captures blue whiting (Martín et al. 2016). Many fishing days correspond to trawlers that operate in fishing grounds different from those of blue whiting. Daily landings combined with vessel monitoring system (VMS) data were used to characterize the areas where the bottom trawl fleet of Catalonia operates, based on the amount of blue whiting landings extracted and the effort applied in each area. VMS is a satellite-based monitoring system that provides data on the location, course and speed of vessels to the fisheries authorities at regular intervals, at least once every two hours, and is compulsory for vessels larger than 12 m. It is important to note that VMS data do not indicate whether the vessels are fishing, steaming or inactive. To filter fishing activity, following methodologies described in previous studies (Bueno-Pardo et al. 2017, Lee et al. 2010, Russo et al. 2014), we applied a speed filter between 1.5 and 5 knots that included the speed range for trawling while excluding steaming and inactive moments. Once we had obtained the fishing VMS data we calculated fishing time per day and vessel (fishing trip) and simultaneously calculated blue whiting landings per fishing trip from the auction landings dataset. We homogeneously associated each variable with VMS fishing points corresponding to the same trip. Finally, we aggregated fishing points and their associated variables in a 1×1 $km^2$ grid. Landings per unit effort (LPUE) (kg/h) were calculated by grid cell and represented in maps.

Blue whiting sampling was conducted on the northern Catalan coast, off Cap de Creus and Roses (Fig. 1). The continental shelf width varies from ~2.6 km near the Cap de Creus canyon, to ~30 km in its wider part (Ribó et al. 2018). The bottom trawl fishing grounds encompass the rather narrow continental shelf, the upper slope and the submarine canyon. Monthly samples, from March 2017 to October 2018, were collected on board a commercial otter bottom trawler (length overall = 25.05 m, gross tonnage = 100.13, power = 367.7 kW; 40 mm squared mesh size at the cod-end) that usually goes fishing to the blue whiting fishing grounds. The fishing gear was equipped with a SCANMAR system, which allowed us to know the depth where it was operating. Two fishing grounds where the trawler regularly operates were visited, at the shelf break, at around 130–250 m depth, and on the upper slope, at 250–550 m depth (Fig. 1). In total, 60 hauls were conducted (28 on the shelf break and 32 on the slope). A temporal closure was implemented in February. No particular indications were given to the skipper, so sampling reflects normal fishing activity. During the recruitment period, from April to July, the sampling of the catch on board was conducted biweekly to ensure that recruitment timing and duration were detected. When sampling on board was not possible because of weather conditions, blue whiting samples were collected at the auction. These samples corresponded to December 2017, i.e. outside the recruitment period, when discards were generated (Mir-Arguimbau et al. 2020b).

All individuals were measured on board to the nearest millimetre (TL) and grouped into 1 cm intervals. The sampling on board revealed the monthly length frequency distributions (LFDs) corresponding to the commercial and discarded catch as well as the monthly ratio of discards to commercial catch, i.e. the amount of discards generated in relation to the fraction of the total catch that was commercialized. The discards were made up of the recruits from the spawning of the same year. Prior to any analysis, LFD data were standardized to n/h (numbers/hour). The total monthly LFDs of the commercial catch, expressed in numbers (thousands), were generated by combining the LFDs from the sampling on board and the monthly landings (tonnes) available from the fishing statistics. The ratio of discards to commercial catch was applied to generate the total monthly discarded catch. The length-weight relationship used was taken from Mir-Arguimbau et al. (2020b).

The monthly LFDs in the two fishing grounds, the shelf break and the slope, were obtained from the

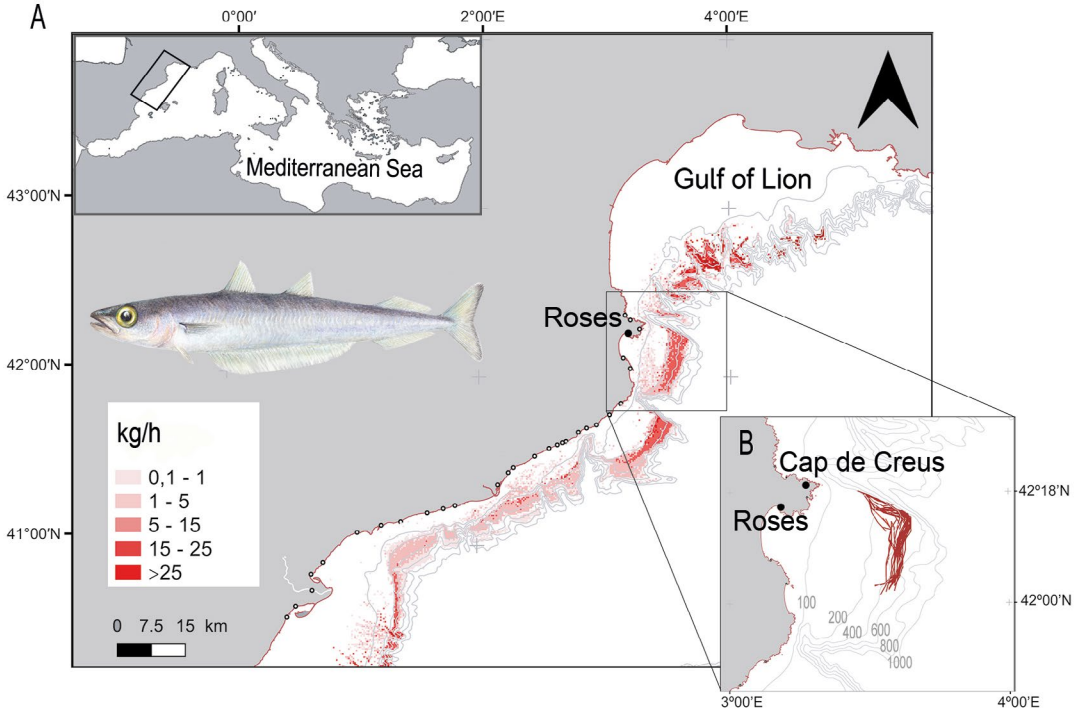


Fig. 1. − Study area. A, production map of blue whiting along the Catalan coast in 2017 defining the species fishing grounds, and B, sampling area off Roses showing the vessel fishing tracks over the shelf break and upper slope. Blue whiting illustration by J.M.-A.

individuals collected in the sampling on board. The age-length key in Mir-Arguimbau et al. (2020b) was applied to the LFDs to convert them to age-frequency distributions. The recruitment timing and area was based on the total monthly LFDs of the commercial and discarded catch and on the monthly LFDs on the shelf break and the slope.

## RESULTS

### Fishing grounds

The spatial distribution of blue whiting landings resulting from the activity of the bottom trawl fleet with reported blue whiting landings is shown on the production map (Fig. 1). The map clearly identified the blue whiting fishing grounds located over the shelf break and the slope, mainly at 200 to 600 m depth. The biomass extraction was highest in the northern areas, up to 25 kg/h, especially in the Gulf of Lion, suggesting that the species would be more abundant to the north. The most productive areas overlapped with the implemented Fisheries Restricted Area (FRA) in the Gulf of Lion (FAO-CGFM 2009) (Fig. 1). It is important to note that the maps refer to the commercialized catch, that is, discards were not included in these maps, and that only the Catalan fleet is represented by this VMS set, so the interaction of fleets from France is not accounted for.

### Landings and LPUE trend

Over the period 2000-2020, blue whiting landings from the Catalan coast and landings and LPUE (landings per fishing day and vessel) from the fishing port of Roses displayed the same trend (Fig. 2). Landings from Roses represented around 20% to 25% of those from the Catalan coast. Overall, landings showed a decreasing trend with fluctuating values, and in the most recent years landings remained at the lowest values of the time series. Blue whiting LPUE from Roses displayed the same trend as landings. Fishing effort, expressed as the number of fishing days with reported blue whiting landings, displayed a steadily decreasing trend to reach a 60% decrease over the whole period (3598 days in 2000 and 1403 in 2020). Despite the progressive decrease in the number of fishing days in the most recent years, blue whiting landings increased slightly in 2019. The LPUE increase observed in 2019 was more marked than that of landings (Fig. 2).

During the first part of the series (2000-2010) with high annual values, the landings in winter and spring large accounted for the annual total, while the landings in summer and autumn were low in relation to those in the first half of the year. However, in years of good recruitment, e.g. 2006, summer-autumn landings were also high because they were dominated by recruits of the year. In the second part of the series, when annual landings were low and interannual variation was low, this seasonal pattern was much less evident (Fig. 3).

### Length frequency distributions

The sizes of the blue whiting captured ranged between 5 and 39 cm TL (Fig. 4). Blue whiting discards corresponded to very small sized individuals (from 5 to 15 cm TL). The size of the smaller discarded individuals (from 5 cm TL) corresponded to the size when

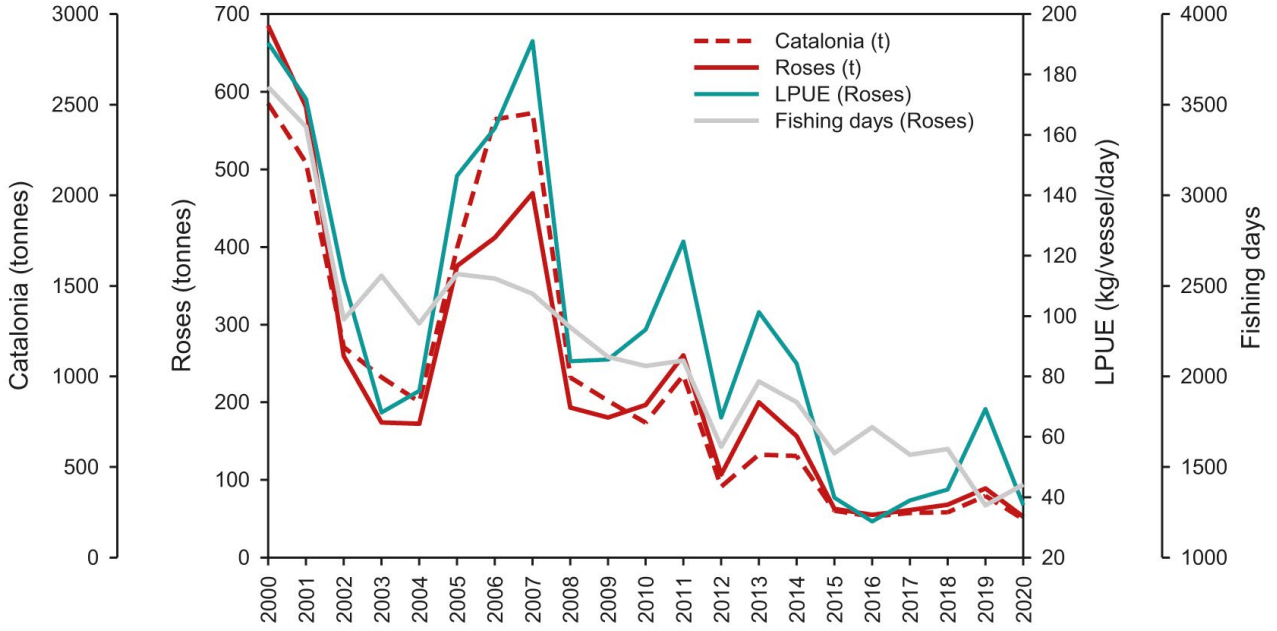


Fig. 2. – Blue whiting annual landings in tonnes on the coast of Catalonia (red-dashed line, left outer axis) and in Roses harbour (red line, left inner axis), LPUE in Roses (kg/day/vessel, green line, right inner axis), and fishing days in Roses (grey line, right outer axis).

blue whiting shifted from the pelagic to the demersal habitat, so discards were taken as an indicator of recruitment to the fishery.

The LFDs showed the dynamics of the species in the area over the year, that is, the time of the year when the incorporation of recruits occurs and large individuals are present in the bottom trawl catch (Fig. 4). The incorporation of recruits that would be discarded, between 5-12 cm TL with the mode at 7-9 cm TL, started in April and was highest in May; later on, the recruits' mode shifted towards larger sizes, and discards decreased in the following months. The time of the year with highest discards was spring, especially May, although some discards were still observed until October (Fig. 4). The larger individuals (>26 cm TL) were more abundant in the coldest period (from January to March); their presence decreased in the following months, and no large individuals were detected in late summer and autumn (from August to December). The period of highest presence of large individuals corresponded to the reproduction period of the species in the area (December-March) (Mir-Arguimbau et al. 2020b).

In the two years of sampling, discards represented a very large fraction of the blue whiting catch, 31% and 23% in 2017 and 2018, respectively, when expressed in weight. These values are very high, but when discards are expressed in number, the percentage of the discarded catch amounted to more than 80% and 75% of the total individuals fished in 2017 and 2018, respectively (Table 1). It is worth mentioning that in May 2017 and 2018 almost the whole catch was discarded (95% and 98%, respectively). In 2017 recruitment took place earlier than in 2018, and consequently discards in April were also very high (94%), while in April 2018 they were quite low (6%) (Table 1).

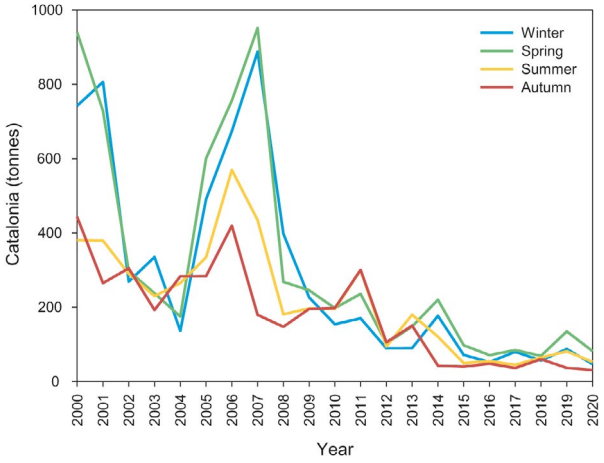


Fig. 3. – Seasonal landings of blue whiting on the coast of Catalonia from 2000 to 2020.

## Spatial distribution by size and age

Blue whiting displayed spatial segregation by size. The smaller individuals (recruits) remained on the shelf break (130-250 m depth), while the large ones (adults) were more abundant on the upper slope (250-550 m). The largest individuals displayed movements over the year. They approached the coast during the spawning period (March 2017 and January 2018) and remained on the upper slope until spring, gradually disappearing from the catches in the following months (Fig. 5).

The age composition of catches ranged between 0 and 8 years, and ages 0-1 were the most abundant ones. Age 0 individuals were clearly dominant in the catches.

A different distribution by age was observed in the two fishing grounds during the year. Ages 0 and 1 were predominantly found on the shelf break, while ages 2 and over were more abundant on the upper slope. Age 0 individuals peaked in April and May, notably in May, on the shelf break and their presence on the slope was very low. The older individuals (from 3 yr) appeared in the catch from January to July, but then gradually decreased and showed practically no presence from August (Table 2).

## DISCUSSION

Blue whiting is considered a cold-water species in the Mediterranean Sea, the southern edge of the species distribution (Bailey 1982). In the area where the Catalan bottom trawl fleet operates, the species is mainly fished in the northern sector of the coast and in the Gulf of Lion (Fig. 1), suggesting that the species is more abundant there than southwards. The higher abundance of cold-water species such as blue whiting in the northern areas of the Mediterranean is a well-documented phenomenon linked to the marked latitudinal gradient of temperatures (Bianchi and Morri 2000, Lloret et al. 2015). The production map allowed us to identify the blue whiting fishing grounds in the NW Mediterranean and evidenced that the species is mainly found between 200 and 600 m depth, as reported in the Atlantic (Bailey 1982, Johsen and Godø 2007). However, it was not possible to determine the distribution of the species at greater depths because at bottom depths greater than 500 m the species is not associated with the seabed, and is therefore not efficiently sampled by bottom trawling.

In the last decade, blue whiting landings on the Catalan coast have displayed a decreasing trend and have remained at very low levels in the most recent years,

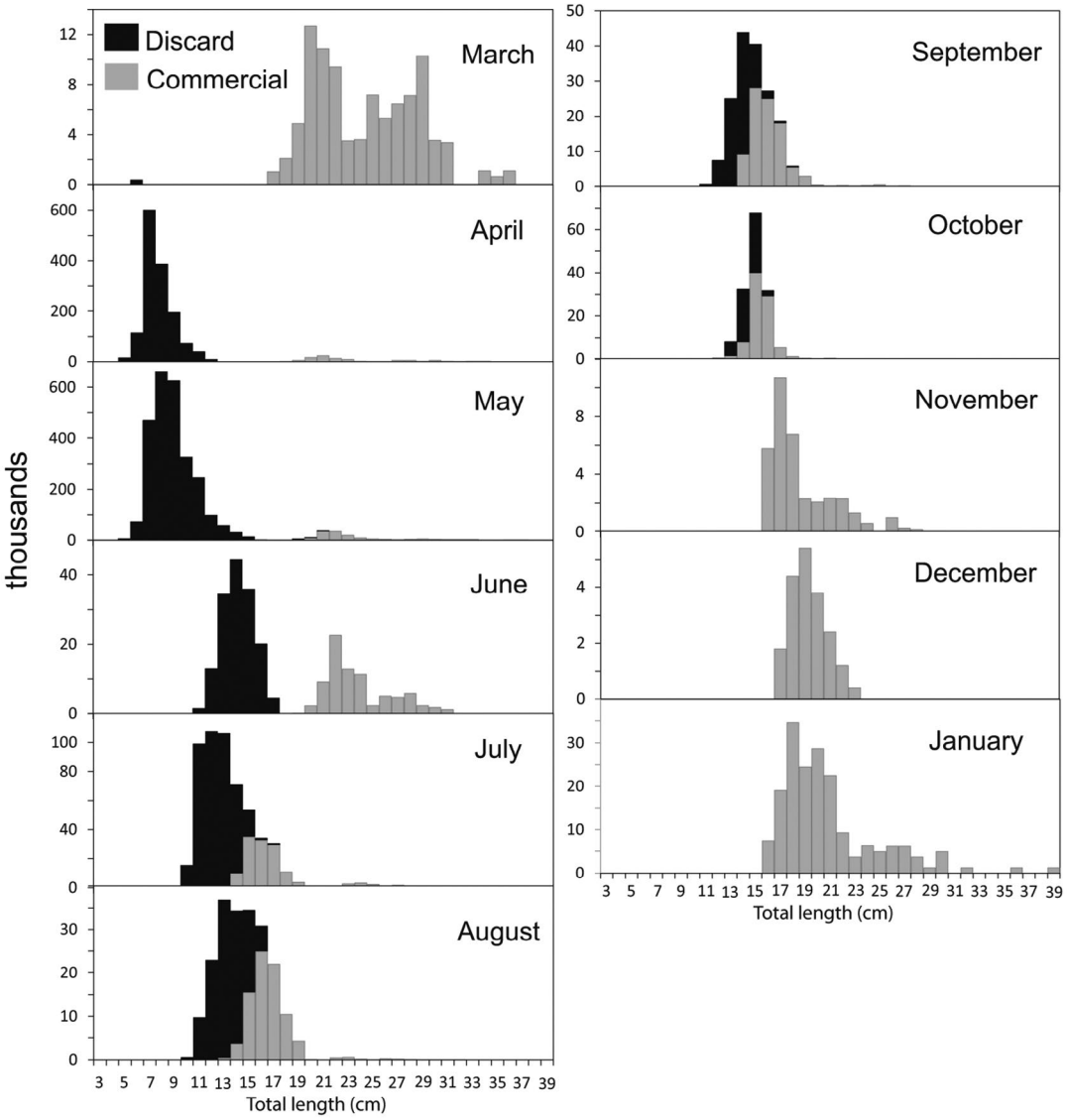


Fig. 4. – Monthly length frequency distributions of the commercial (grey) and discarded (black) blue whiting catch in the fishing port of Roses from March 2017 to January 2018. A temporal closure for bottom trawling was implemented in February. A minimum conservation reference size was set to 15 cm TL on the Catalan coast. Note the different scales of the Y-axis.

lower than the minimum values reported by Martín et al. (2016) over the period 1961–2011. These authors also reported cyclic fluctuations in the landings linked to deep convection processes that occur in the Gulf of Lion in winter (MEDOC group 1970). These processes enhance planktonic production and subsequent recruitment of the species, resulting in a strong year class the following year (Martín et al. 2016). The low landings observed in the last few years might be related to the absence since 2013 of intense deep convention processes in winter (Salat et al. 2019, Margirier et al. 2020), which enhance landings peaks. Major episodes (deep convection down to 1800 m depth) were detected again in winter 2018 (Margirier et al. 2020), resulting in a slight increase in landings in 2019 (more marked in the LPUE). However, this increase was lower than those previously observed after deep convection episodes (Martín et al. 2016), pointing to a weak response of the stock to the favourable environmental conditions. Indeed, in 2020, with fishing effort (fishing days) similar to that in 2019, LPUE was much lower. The effects of the exploitation on this weak blue whiting response in 2019 to the deep convection of the previous year cannot be disregarded, particularly when landings display a decreasing trend and the bulk of the catch is made up of immature individuals (size of first maturity 18-19 cm TL; Serrat et al. 2019, Mir-Arguimbau et al. 2020b).

Blue whiting LFDs showed marked changes over the year and between areas. The larger individuals appeared in the winter months over the upper slope, and the massive incorporation of recruits took place in spring, basically in May, over the shelf break. The presence of large individuals corresponds to spawners (age ≥2) that approach the upper slope for reproduction in

Table 1. − Blue whiting monthly commercial and discarded catch in the fishing port of Roses, in weight (tonnes) and number (thousands) in 2017-2018. Discards % in relation to the total catch are shown (data source: landings from Fisheries Service of the Generalitat de Catalunya and discards estimated from sampling onboard).

| | | Weight (t) | | | Number (thous.) | | |
|---|---|---|---|---|---|---|---|
| | Month | Commercial | Discards | % discards | Commercial | Discards | % discards |
| 2017 | 1 | 6.6 | 0.0 | 0.0 | 131.4 | 0.0 | 0.0 |
| | 2 | | | | | | |
| | 3 | 10.6 | 0.0 | 0.0 | 94.3 | 0.4 | 0.4 |
| | 4 | 8.4 | 4.0 | 32.3 | 90.7 | 1428.8 | 94.0 |
| | 5 | 12.4 | 12.1 | 49.4 | 135.8 | 2604.4 | 95.0 |
| | 6 | 7.8 | 2.8 | 26.5 | 80.4 | 153.4 | 65.6 |
| | 7 | 4.7 | 4.9 | 50.9 | 136.9 | 407.1 | 74.8 |
| | 8 | 2.6 | 1.9 | 42.3 | 83.6 | 124.2 | 59.8 |
| | 9 | 2.5 | 1.4 | 35.0 | 90.9 | 82.3 | 47.5 |
| | 10 | 2.1 | 1.2 | 35.9 | 87.2 | 60.9 | 41.1 |
| | 11 | 1.6 | 0.0 | 0.0 | 35.6 | 0.0 | 0.0 |
| | 12 | 0.9 | 0.0 | 0.0 | 19.4 | 0.0 | 0.0 |
| | Total | 53.8 | 28.2 | 34.4 | 986.2 | 4861.5 | 83.1 |
| 2018 | 1 | 13.0 | 0.0 | 0.0 | 186.6 | 0.0 | 0.0 |
| | 2 | | | | | | |
| | 3 | 11.6 | 0.0 | 0.1 | 155.4 | 7.7 | 4.7 |
| | 4 | 6.3 | 0.0 | 0.2 | 80.3 | 5.3 | 6.2 |
| | 5 | 5.8 | 14.8 | 71.9 | 35.6 | 2900.4 | 98.8 |
| | 6 | 9.4 | 0.7 | 7.3 | 103.2 | 32.2 | 23.8 |
| | 7 | 12.3 | 0.4 | 3.3 | 350.2 | 21.0 | 5.7 |
| | 8 | 4.1 | 0.8 | 16.6 | 79.1 | 40.9 | 34.1 |
| | 9 | 4.0 | 3.6 | 47.5 | 135.6 | 187.0 | 58.0 |
| | 10 | 4.0 | 0.0 | 0.0 | 96.9 | 0 | 0.0 |
| | 11 | 5.6 | 0.0 | 0.0 | | | |
| | 12 | 4.8 | 0.0 | 0.0 | | | |
| | Total | 80.8 | 20.4 | 20.2 | 1222.8 | 3194.6 | 72.3 |

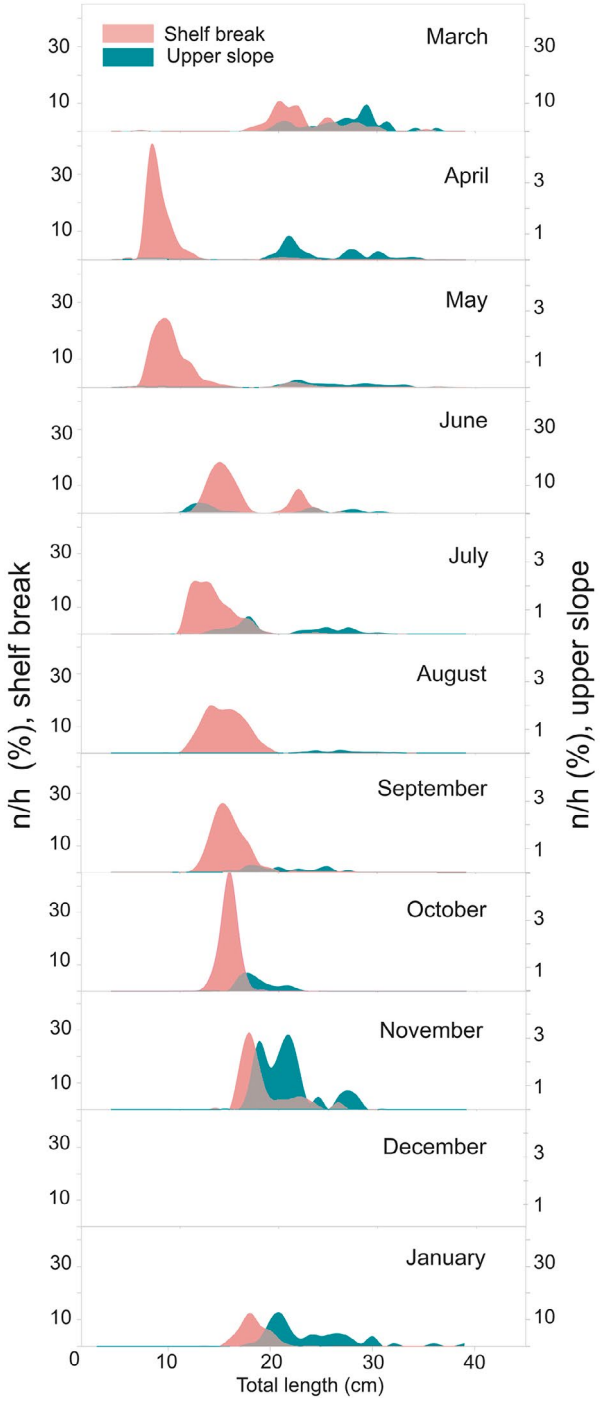


Fig. 5. – Monthly length frequency distributions of the total catch of blue whiting (commercial+discards) over the shelf break (pink) and upper slope (green) from March 2017 to January 2018, expressed in percentage. Note the different scale of the right axis in March, June and January. No data are available for December 2017.

winter (Table 2; Fig. 5, March 2017 and January 2018), joining the resident population that is mainly composed of age 0 and 1 individuals. The spawning over the upper slope would allow the blue whiting eggs and larvae to be retained by the shelf-slope density front that is present all along the continental slope (Font et al., 1988), avoiding their dispersion towards the open sea (A. Sabatés, pers. comm.), as observed in other fish species in the area (Sabatés et al. 2018). Thus, the fluctuations in the presence of large individuals over the year would suggest population movements linked to reproduction, as already described for the blue whiting in the Atlantic (Bailey 1982, Hátún et al. 2007). These displacements over the year and recruitment intensity and period would explain the seasonal pattern of landings. The seasonal pattern changed in the period 2000-2020. Marked peaks were detected in winter-spring in years of high landings, but when annual landings remained at very low levels, as of 2008, this seasonal pattern became less pronounced (Fig. 3). The disappearance of the marked winter-spring landings peak must reflect a low recruitment the previous year i.e. a low abundance of age 1, as well as a low abundance of spawners.

The spawning stock must remain on the upper slope in spring, the recovering season (Serrat et al. 2019, Mir-Arguimbau et al. 2020b), gradually disappearing from the landings in the following months (Fig. 5; Table 2). This means that the spawning and feeding grounds in the Mediterranean overlap, unlike in the Atlantic, where migrations linked to feeding and reproduction have been described (Bailey 1982, Hátún et al. 2007). The absence of these large individuals in the catch some months after spawning would suggest that blue whiting move to areas not accessible to bottom trawl. In agreement with our results, in the Aegean Sea, where the spawning season spans from December to March, the presence of large individuals was observed in December and March, yet their presence was much lower in June (Papaconstantinou and Petrakis 1989). While we cannot describe the direction of the population migratory movements, we could expect inshore-offshore movement of the species at a certain depth, i.e. without a close association with the seabed when the depth exceeds 500 m (Johsen and Godø 2007). Indeed, inshore-offshore displacements of spawners have been hypothesized for the Portuguese coast (Gonçalves et al. 2017). Also, considering that blue whiting is closely associated with the shelf-slope region, and a strong connectivity along this axis has been reported in the Atlantic (Post et al. 2019), we cannot disregard northward movements in summer to the Gulf of Lion where, based on the production map, the species is more abundant than southwards (Fig. 1). In this regard, the presence of large individuals has been reported in autumn in the Gulf of Lion (Massuti et al. 2008). However, we can only hypothesize about these possibilities, since our information comes from the commercial bottom trawl, for which blue whiting is not a fishing target, and no specific surveys are available for the species in the NW Mediterranean.

Our results show that the highest blue whiting yields were obtained in the Gulf of Lion, some of them in the FRA established in 2009 to protect spawning aggregations and sensitive deep-sea habitats (FAO-GFCM 2009). Since then, fishing effort in the FRA has been frozen. A bottom trawl survey conducted in autumn 2007 in an area that was later protected showed higher abundance than that observed in the commercial catch of large individuals of the different target spe-

Table 2. − Blue whiting monthly age composition of the individuals (number/hour) on the shelf break (S b) and the upper slope (U s) from October 2016 to October 2018.

| | Age (year) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | Zone | | | | | | | | | |
| 2016-Oct | S b | | | | | | | | | |
| 2017-Mar | S b | 67.6 | 111.7 | 25.4 | 7.0 | 3.7 | 4.8 | 0.2 | 0.1 | |
| 2017-Apr | S b | 2732.4 | 41.7 | 0.8 | 0.0 | | | | | |
| 2017-May | S b | 5594.4 | 187.8 | 6.5 | 0.1 | | | | | |
| 2017-Jun | S b | 526.7 | 121.6 | 6.6 | 0.4 | | | | | |
| 2017-Jul | S b | 3467.3 | 122.4 | 6.4 | 0.7 | 0.0 | | | | |
| 2017-Aug | S b | 879.4 | 57.5 | 0.1 | | | | | | |
| 2017-Sep | S b | 767.2 | 43.8 | | | | | | | |
| 2017-Oct | S b | 583.6 | 24.2 | | | | | | | |
| 2017-Nov | S b | 55.9 | 23.7 | 1.3 | 0.2 | | | | | |
| 2016-Oct | U s | 101.8 | 36.6 | 0.9 | 0.2 | | | | | |
| 2017-Mar | U s | 14.5 | 56.5 | 50.5 | 21.3 | 18.3 | 11.3 | 5.8 | 1.2 | 1.5 |
| 2017-Apr | U s | 27.7 | 48.2 | 15.7 | 8.2 | 7.3 | 4.6 | 1.6 | 0.6 | 0.3 |
| 2017-May | U s | 18.9 | 50.5 | 18.3 | 8.3 | 9.6 | 6.1 | 2.2 | 0.2 | 0.5 |
| 2017-Jun | U s | 805.4 | 31.9 | 17.4 | 5.3 | 3.1 | 1.7 | 0.3 | 0.1 | |
| 2017-Jul | U s | 62.4 | 34.8 | 14.4 | 3.5 | 1.4 | 0.7 | 0.1 | 0.1 | |
| 2017-Aug | U s | 0.1 | 2.5 | 1.5 | 0.5 | 0.2 | 0.1 | 0.0 | 0.0 | |
| 2017-Sep | U s | 6.3 | 6.7 | 1.5 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | |
| 2017-Oct | U s | 12.0 | 4.2 | 0.0 | | | | | | |
| 2017-Nov | U s | 6.9 | 6.8 | 1.0 | 0.2 | 0.1 | 0.0 | | | |
| 2018-Jan | S b | 39.4 | 17.0 | 0.1 | 0.0 | | | | | |
| 2017-Mar | S b | 201.7 | 200.1 | 12.0 | 4.8 | 3.9 | 2.0 | 0.8 | 0.1 | |
| 2018-Apr | S b | 89.4 | 177.8 | 7.3 | 0.2 | | | | | |
| 2018-May | S b | 4923.0 | 2.9 | 0.7 | 0.1 | 0.0 | 0.0 | | | |
| 2018-Jun | S b | 146.5 | 72.4 | 12.1 | 1.2 | 0.0 | | | | |
| 2018-Jul | S b | 3080.0 | 621.0 | | | | | | | |
| 2018-Aug | S b | 113.9 | 12.3 | | | | | | | |
| 2018-Sep | S b | 949.2 | 26.6 | | | | | | | |
| 2018-Oct | S b | 892.4 | 374.2 | | | | | | | |
| 2018-Jan | S b | 20.6 | 44.8 | 12.9 | 4.8 | 2.5 | 1.5 | 1.3 | 0.1 | 1.6 |
| 2017-Mar | U s | 2.0 | 33.6 | 25.8 | 6.6 | 3.6 | 2.1 | 0.6 | 0.1 | 0.1 |
| 2018-Apr | U s | | 0.9 | 3.8 | 3.5 | 4.2 | 2.7 | 1.7 | 0.3 | 0.3 |
| 2018-May | U s | 1.2 | 15.5 | 14.4 | 9.2 | 8.6 | 6.0 | 2.2 | 0.3 | 0.1 |
| 2018-Jun | U s | 29.4 | 35.9 | 19.0 | 4.5 | 2.3 | 1.4 | 0.4 | 0.1 | 0.0 |
| 2018-Jul | U s | 0.9 | 35.5 | 31.1 | 10.7 | 6.5 | 3.4 | 1.4 | 0.3 | 0.1 |
| 2018-Aug | U s | 1.1 | 25.0 | 13.9 | 2.9 | 0.9 | 0.6 | 0.1 | 0.0 | 0.1 |
| 2018-Sep | U s | 28.1 | 31.6 | 7.4 | 1.8 | 0.7 | 0.4 | 0.0 | 0.0 | |
| 2018-Oct | U s | | | | | | | | | |

cies, one of them, blue whiting (Massuti et al. 2008). The abundance of large individuals points to a healthy status of the population. As stated in Commission Decision 2017/848 (EU 2017), a high proportion of old/large individuals in the populations of commercially-exploited species is indicative of a healthy population. In the Gulf of Lion, based on trawl surveys, an east-to-west gradient was reported regarding average sizes and abundances of target species. The gradient was smaller in the western part, where the French and Spanish fleets operate, than in the eastern part, where fishing effort is lower (UNEP-MAP-RAC/SPA 2013). These findings, combined with the established FRA, suggest that the Gulf of Lion might act as a refuge for the species (Farrugio 2012).

In 2010 a change in the mesh size was introduced, from 40 mm diamond to 40 mm square mesh size, which in principle would improve protection of the smallest individuals in comparison with the first part of the study period (2000-2010). However, the results of the present study show that blue whiting recruits were highly fished and discarded during the second period. Ancillary information on blue whiting LFDs of the total catch is available from research projects conducted in the study area in the 1980s (Martín 1989, Lleonart 1990). Despite the changes in the gear design and mesh size (smaller at the time) it is worth noting that the smaller reported exploited sizes started at 9 cm TL, and abundance of large individuals was higher than at present. Data from the 1960s indicate that the exploited sizes ranged between 12 and 32 cm TL (Bas 1963), the larger sizes being absent from the catch because of limited access to the deeper fishing grounds. Blue whiting has been exploited for several decades with immature individuals (size at first maturity around 18 cm TL; Serrat et al. 2019, Mir-Arguimbau et al. 2020b) as a major component of the catch. In the present study, the age composition of the catches ranged between 0 and 8 years, ages 0-1 being the most abundant ones. Fishery-independent data from 2009-2013 reported that the blue whiting population consisted mainly of only four age classes, from 0 to 3, the abundance of ages 2 and 3 being very low (STECF 2014). These age compositions indicate that the species has been heavily exploited for years, and the maintenance of the population is almost exclusively dependent on recruitment. Furthermore, since the reproductive potential of blue whiting increases with size (Serrat et al 2019), the scarcity of large fish must have also affected the reproductive potential of the population.

Recruitment to the demersal habitat takes place over the shelf break in April and May, when the individuals attain 5 cm TL, and the recruits remain there until the next spawning season (Fig. 4). This size is smaller than the recruitment size previously reported for the western Mediterranean, 11 cm TL in June (García et al. 1987). Tursi et al. (1992) identified blue whiting nursery areas in the Ionian Sea located at 100-300 m depth. Recruits, 8-9 cm individuals in April-May, and 11-12 cm individuals in June, represented between 30% and 96% of the sampled population. These observations on blue whiting attaining 11 cm TL in June suggest a rather regular pattern of the species in the Mediterranean in relation to the recruitment timing, location and size.

In the present study, the major component of the blue whiting discards corresponded to individuals between 5 and 12 cm TL, coming from the recent spawning (Table 2 and Fig 3). Discards were observed over a period of several months, from April to October, associated with the seasonality of the recruitment, but very high discards were concentrated mainly in the month of May (more than 95% of the catch in number, Table 1). These discard values are much higher than those previously reported in the Mediterranean to date by Tsagarakis et al. (2017). In their review on Mediterranean discards, these authors stressed that the bottom trawl discard ratios of non-target commercial bycatch species such as blue whiting were higher than those of the target species. Blue whiting discards rates of less than 5% of the catch have been reported in the Ligurian Sea, discards consisting of individuals ranging between 10 and 19 cm TL (STECF 2014, Mannini and Lanteri 2015). A similar size range for blue whiting discards, 13 to 19 cm TL, has been reported for the deep-sea decapod crustacean fisheries in Mallorca (Moranta et al. 2000). Blue whiting discards in the Atlantic, where the species is fished almost entirely with pelagic trawl (99% of the catch) are reported to be very low (0.25% of the catch) (ICES 2019). Altogether, the reported discard values make blue whiting one of the species with the highest discards in bottom trawl fisheries in the Mediterranean. This finding constitutes an important input for the implementation of the ecosystem approach to fisheries management because it highlights that the impact of fishing activity on the ecosystem might be underestimated when the exploitation status of bycatch species is not taken into account.

The results of the present study suggest that blue whiting is intensively exploited in the NW Mediterranean. This is evidenced by the decline in landings over the last decade, the catch dominated by immature individuals and the very low presence of old, large-sized blue whiting. Considering that larger females have a higher reproductive success than smaller females (Hixon et al. 2014, Serrat et al. 2019), the scarcity of large individuals must have also affected the reproductive potential of the population. Furthermore, it is precisely during the reproductive period that the large and more fecund individuals are caught, which must have further worsened the status of the stock. Indeed, the most recent stock assessment of blue whiting in the western Mediterranean, performed some years ago (STECF 2014), reported that the stock was highly over-exploited. To improve the status of fish stocks, the fishing pressure on immature individuals must decrease (Vasilakopoulos et al. 2011) which, according to our results, is not the case for NW Mediterranean blue whiting. The implementation of closures in spring, when the highest discards rates have been observed, should be considered as a management measure for the recovery of the population. Though the above indicators point to over-exploitation, there part of the population may not be accessible to bottom trawling, because the larger individuals disappear from the catch for several months.

In addition to fishing, the unfavourable environmental conditions, such as the absence of deep convection processes for a period of eight consecutive years (Margirier et al. 2020), must have negatively impacted the species. In fact, the response of blue whiting to the deep convection in 2018 was rather weak, suggesting that low levels of abundance might have hindered their reaction to favourable environmental drivers. We must also consider that for a species with affinity to cold waters, with a strong dependence on the cold winter temperatures for reproduction in the Mediterranean (Mir-Arguimbau et al. 2020b), the sea water temperature increase recorded (Salat et al. 2019) must have been be an additional stress (Lloret et al. 2015). All these environmental constraints, added to over-exploitation and their synergistic effects, must have affected the resilience of the species, compromising its success in the Mediterranean.

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