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Title: Growth, reproduction and their interplay in blue whiting
(*Micromesistius poutassou*) from the NW Mediterranean

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Growth, reproduction and their interplay in blue whiting (*Micromesistius poutassou*, Risso, 1827) from the NW Mediterranean

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Abstract

Life-history traits as growth, age at first maturity, reproduction and condition as well as the size distribution of the commercial and the discarded catch, have been studied for the blue whiting, *Micromesistius poutassou*, from the NW Mediterranean. This is a species of commercial interest in the area. In the last decade its landings remained at very low levels and the stock has not shown signs of recovery. Samplings were conducted monthly in the northern Catalan coast on board a commercial bottom trawler, from October 2016 to October 2018. The results showed a high variability in the size at age. The size at first maturity was around 18 cm for both sexes that is achieved when the species completes its first year of life, that is, the spawning season following its birth. Females and males showed different growth curves, with females reaching higher sizes than males. From 25 cm TL females became dominant in the population. The readings of lapilli otoliths of very young individuals (from 42 to 87 days old) allowed an accurate estimate of the growth parameters. The diameter of the first annual ring in

the sagitta otoliths was defined for the NW Mediterranean (9.8 ± 0.74 mm). The diameter of the observed two false annual rings were also provided. This study has also shown a close relationship between reproduction, condition and stomach fullness trends, which, in turn, have been observed to be related with the changes in the species growth during the year. Finally, the study allowed knowing the very high amount of blue whiting discards. The main component of catches (in numbers) corresponded to discarded individuals, and, in addition, the minimum landing size implemented in the study area is smaller than the size at first maturity.

Keywords

Life-history traits; age determination; Otoliths; Length distribution; Discarded catch

Highlights

High variability in the size at age of Mediterranean blue whiting
Blue whiting recruits to the demersal habitat at sizes between 3 and 7 cm TL
There is a trade-off between the energy invested in growth and reproduction
Most of the catch corresponds to immature and undersized individuals

1. Introduction

Blue whiting, *Micromesistius poutassou* (Risso, 1827), is a pelagic gadoid widely distributed in the North Atlantic and the Mediterranean Sea, inhabiting over the shelf edge and continental slope (Bailey, 1982; Heino et al., 2008). There is large amount of information on its biology, behavior and fisheries for the Northeast Atlantic (Bailey and Heath, 2001; Bailey, 1982; Gonçalves et al., 2017; Hátún et al., 2009; Payne et al., 2012), but less is known for the species in the Mediterranean despite it has an important commercial interest, particularly in the northern part (Bas, 1963; Bas and Calderon-Aguilera, 1989; Martin et al., 2016; Orsi-Relini and Peirano 1985; Serrat et al., 2019). According to stock identification techniques, the Mediterranean population is considered isolated from the Atlantic population (Pointin and Payne, 2014). Thus, the knowledge of the biological features of the Mediterranean blue whiting is essential, not only to provide a basis for the understanding of its population dynamics, but also to achieve a sustainable exploitation of its fisheries.

Blue whiting plays an important role in the marine food web. The species feeds on pelagic crustaceans and Myctophidae fish (Macpherson, 1978; Papiol et al., 2014) and, as prey, it is consumed by a wide range of predators, such as fish (*Merluccius merluccius*, *Lophius* spp. and *Scomber scombrus*) (Karlovak, 1959; Silva et al., 1997), sharks (*Squalus acanthias*), and squids (*Todaropsis* and *Ommastrephes*) (Bailey, 1982). In the North Atlantic, major migrations of the species were reported linked to reproduction (Bailey, 1982; Hátún et al., 2007), however, within the Mediterranean such migrations have not been described (Martin et al., 2016). In the Atlantic the spawning of the species takes place a temperature around 11°C (Seaton and Bailey,

1971) and 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 NW Mediterranean, the spawning occurs in winter, from December to March (García et al., 1981; Serrat et al., 2019), when temperatures reach the minimum values (12-13 °C) (Calvo et al., 2011). Blue whiting presents a fast growth during the first year of life, reaching sizes around 20 cm in the Mediterranean and Atlantic waters (Bas, 1959; Monstand, 1990). Differences in growth by sex have been reported, with highest growth rates and larger sizes for females than males (Monstand, 1990; Trenkel et al., 2015).

In the Mediterranean, blue whiting constitutes a traditional fisheries resource and is captured by the bottom trawl fleet over the shelf break and the upper slope, mainly at 200–400 m depth (STECF, 2014; Martín et al., 2016). It is mainly fished in the Northern colder waters of the Mediterranean (Gulf of Lions and Catalan Sea in the western part, and in Ligurian-Tyrrhenian, Adriatic and Aegean Sea in the central and eastern Mediterranean). In the NW Mediterranean basin, a peak in blue whiting landings was reported during the early 80's around 10000 t and until 2011 the landings fluctuated around 4000 t (Martín et al., 2016). In the Northern Catalan coast, landings have been shown to display cyclic fluctuations (around 2000 annual tones) linked to winter hydrodynamic conditions that enhance planktonic production and recruitment of the species (Martín et al., 2016). However, during the last decade, the periodicity in landings was no longer observed, and the stock remains at low levels showing no signs of recovery (around 250 annual t, according to the statistics of the Fisheries Department of Autonomous Government of Catalonia (Generalitat de Catalunya, 2019).

Fishing is a selective process that preferentially removes older/larger individuals. Age truncated populations display a demographic structure dominated by fewer and younger age classes, which may affect the population dynamics through different pathways (Rouyer et al., 2011). Removing larger and older individuals may substantially alter the reproductive output of populations through maternal effects. Berkeley et al. (2004) demonstrated that older females produce a relatively greater number of eggs and larvae with a higher growth and survival. For those stocks with highly episodic recruitment, such as blue whiting, the consequences of age-class truncation may be catastrophic (Longhurst, 2002). Therefore, fish age determination and the population age structure provides information that is essential for knowing the state of population and for an effective fishery management.

The aim of this work was to update the population parameters of *M. poutassou* in the NW Mediterranean, describe the species growth and address the inter-relationships among growth, reproduction and energy reserves. This biological knowledge is essential for assessing the stock status of the species and developing an integrated management strategy for the sustainability of the fishery.

2. Material and methods

2.1 Fish sampling and laboratory protocols

Sampling of *M. poutassou* was conducted in the northern Catalan coast (northwestern Mediterranean) on board a commercial bottom trawler based on the fishing port of Roses, that usually goes fishing to the blue whiting fishing grounds (Fig. 1). The vessel

used was the same along the whole sampling period (length overall (m) = 25.05, gross tonnage = 100.13, power KW = 367.7). The characteristics of this trawler are the same as those of the other trawlers fishing blue whiting in the area. Samples were obtained with a commercial fishing net (otter bottom trawl 40 mm squared mesh size at the cod-end). Two fishing grounds were visited all along the year, at the shelf edge, at around 130 - 250 m depth, and the upper slope, at 250-550 m depth (Fig 1), where the trawler usually operates. In total, 60 hauls were conducted (28 on the shelf edge and 32 on the slope). Monthly samples of the catch were collected by observers on board from October 2016 to October 2018, except in February, when a seasonal closure is implemented (Table S1). No particular indications were given to the skipper, and thus 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 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 that takes place daily upon the arrival of trawlers to the port base. These samples were exclusively collected in the period November 2016-January 2017 and December 2017, i.e. outside the recruitment period, when discards are generated.

All individuals were measured on board to the nearest millimeter (total length, TL). The sampling on board allowed knowing the monthly length frequency distributions (LFD) corresponding to the commercial and discarded catch. Specimens were grouped into 10 mm intervals. The blue whiting monthly landings from the fishing port of Roses were taken from the statistics of the Fisheries Department of Autonomous Government of Catalonia. By combining these data it was possible to generate the total monthly and

annual catch and corresponding LFDs, adding to the landings the discarded catch. Prior to any analysis, LFD data were standardized to n/h.

A subsample of the blue whiting catch was stored in portable coolers and transported to the laboratory. Fifty individuals per haul, that represented the whole sample size range, were selected for biological examination. The following measures were taken: total length (TL), total weight (W) and eviscerated weight (We), to the nearest 0.1 g, and gonad weight (GW), liver weight (LW) and stomach weight (SW), to the nearest 0.01 g.

2.2 Population parameters

Maturity stages were determined by macroscopic examination of the gonads using the six-stage maturity scale proposed by Nikolsky (1963): 1) Immature, 2) Quiescent, 3) Ripening, 4) Ripeness, 5) Reproduction, 6) Spent.

Size-at-first maturity L_{50} , the size at which 50% of individuals are mature, was estimated based on 532 females and 424 males, collected between November (when immature, resting and starting gonad maturation individuals were observed) and April (when the presence of post-spawning individuals was still detected). Data on size and maturity stage were used to fit a predicted proportion of mature individuals at size using binary logistic model. Maturity stages 4-6 were considered.

A total of 2761 individuals (1415 females and 1346 males), collected all along the sampling period, were used in the calculation of the sex ratio. Sex ratio is expressed as the percentage of females in relation to the total number of males and females, by size.

The following indices were calculated: the gonadosomatic index ($GSI = (GW/We) \times 100$), hepatosomatic index ($HSI = (LW/We) \times 100$), and the relative condition index (Kn) (Le Cren, 1951). Kn was calculated as $Kn = We/Wr$ where We is the eviscerated weight of an individual and Wr is the theoretical weight of an individual of a given length (TL in mm) predicted by the length–weight relationship.

The Stomach Fullness (F) was computed as $F = 100 * (SW / We)$ (Hyslop, 1980).

2.3 Growth and age determination

The parameters of the length-weight relationships were calculated using the relationship $W = a * TL^b$, where W is weight (W and We) and TL is total length. Parameters a and b were estimated, for both sexes combined and for females and males separately, using linear regression through logarithmic transformation. Differences by sex in the length-weight relationship were tested (t student for comparison between the regression slopes, parameter b). The length-weight relationships were used in the transformation of catch into numbers ($TL-W$) and in the calculation of the condition factor Kn ($TL-We$).

For age determination, sagitta otoliths of monthly subsamples (5 males and 5 females per cm) were removed. We analysed both the commercial and discarded catch, so that all population sizes were represented. In total, 1449 sagittal otoliths were read, details are given in table 1. In addition, the lapilli otoliths of 48 juveniles (between 5.1 and 12.7 cm TL) were also analysed to determine the age in days. The lapilli were selected due to its smaller size and simpler preparation for daily readings than sagittal otoliths (Secor et

al., 1992). Otolith processing was performed at CEAB's Otolith Research Lab (www.ceab.csic.es/en/otolith-research-lab-2).

The sagitta otoliths were removed, cleaned and stored dry on vials. To enhance contrast between translucent and opaque bands, sagitta were soaked in fresh water at least 24 hrs. before reading. Each pair of sagitta of each specimen was analysed immersed in water over a black surface under reflected light. All sagitta were photographed with a Euromex camera connected to a PC under an optical stereomicroscope (MOTIC SMZ-171) at low magnifications. The following measures were taken: otolith size, number of translucent rings, diameter of the first annual ring and diameter of false inner rings, when apparent (Fig. 2). These false annual rings were measured as additional information for a reliable identification of the first annual ring. The relationship between fish TL-otolith length was established. In addition, the otolith edge condition was recorded. The edge condition (percentage of otoliths with an opaque margin each month) was analysed in 942 individuals from ages 1 to 8 in order to determine the periodicity and timing of ring formation. This method allowed the annual formation of the rings to be determined.

The lapilli otoliths of juveniles were extracted from the head of the fish preserved in ETOH 95% and subsequently attached to a microscope slide using thermoplastic glue (Crystalbond 509). To visualize the daily increments, the lapilli otoliths were polished using different grained sandpapers (from 30 μm to 1 μm Imperial lapping film, 3M) to obtain a thin section with all the rings and the nucleus. Counting of otolith daily increments was performed using a high-powered microscope with transmitted light (Motic BA410E) connected to a Euromex camera and an image analysis system

(ImageFocusAlfa) (Fig. 2). One experienced reader read the otoliths (sagitta and lapilli) two times, leaving enough time between readings to avoid having a reference. If these 2 blind readings differed, a third reading was performed and subsequently the sample was accepted or rejected. The daily readings were considered to estimate the growth parameters and to determine the hatch date of juveniles. We followed ICES (2017) recommendations regarding blue whiting age determination.

As we could easily follow the individuals that enter during the year into the fishery (YOY, Young of the Years) since they presented a clear distinct otolith morphology (Fig. 2), we aged them as a year fraction considering 1st January to be the date of birth and taking into account the month of capture.

The von Bertalanffy growth function (VBGF) was used to describe the growth of the population: $L_t = L_{\infty} (1 - e^{-k(t-t_0)})$ where L_t is the length at age t , L_{∞} is the asymptotic total length, k is the growth coefficient which determines how fast the fish approaches L_{∞} , and t_0 is the theoretical age at which length is zero. The VBGF was fitted to the observed length at age data. In addition, the daily readings and YOY were also included in the input data for the estimation of the growth parameters. These parameters were estimated for males, females and sex combined, using FISAT II with the option that minimizes non-linear least squares with Marquardt's algorithm (<http://www.fao.org/fishery/topic/16072/en>) (FAO, 2013). The criteria for the selection of parameters were lowest standard error of estimates, L_{∞} close to the mean values of the maximum observed lengths, and t_0 that best fitted the daily readings, that are very high quality data. Differences in growth between males and females were tested with the Hotelling T^2 test. A Growth Performance Index $\phi = \log_{10}k + 2\log_{10}L_{\infty}$ was calculated

to allow comparison among the growth parameters estimated in this study with those obtained for the species in other areas and, also, with the growth parameters estimated for other Gadidae species (Source: <https://www.fishbase.se/popdyn/PopGrowthList.php?ID=31&fc=183&genusname=Micromesistius&speciesname=poutassou>) (Froese and Pauly, 2019).

3. Results

3.1 Blue whiting catch

Landings in the fishing port of Roses amounted to 51.2 t and 53.5 t in the first and second sampling years. The length frequency distribution of commercial and discarded catch, monthly available from the sampling on board, allowed estimating the amount of discards generated during these two years. Discards were observed from April to October, the highest values corresponded to May (ca. 50% of the total catch), decreasing the following months (Fig. 3). The discarded catch amounted to 28.2 t (32 % of the total catch) and 20.4 t (20 % of the total catch) in 2017 and 2018, respectively.

The smallest fish size was 3 cm TL, measured in April 2018, and the largest ones were 39 cm TL for females and 34 cm TL for males (Fig. 4). The most abundant sizes ranged between 7-11 cm TL, with a peak at 8 cm TL (with more than 900 thousand individuals).

3.2 Population parameters

Size-at-first maturity L_{50} was estimated at 17.7 cm TL for females and slightly larger, 18.3 cm TL, for males. Sex ratio remained around 0.5 in the size range 12.0-24.0 cm TL. From 25 cm TL females became dominant in the population (Fig 5).

According to the macroscopic observation of gonad maturation and GSI of females, the reproductive period extended over several months, from November-December to March-April, with highest intensity in the winter months (Fig. 6 and 7). GSI was highest in January while because of the temporal closure in February it was not possible to know the GSI in this month (Fig. 6). GSI in March 2018 was highest than in March 2017, and the presence of spent gonads was observed in April 2018 but not in April 2017. These observations suggest that reproduction ended later in 2018 than in 2017. HSI and Le Cren Condition index displayed similar trends, opposite to that of GSI. The highest values were detected around May-June, decreased progressively during summer, recovered slightly in autumn and notably decreased during the spawning period when the minimum values were attained (Fig. 7). This seasonal pattern was similar in both sampling years.

3.3 Growth

According to the L-W and L-We relationship parameters, blue whiting presents positive allometric growth ($b > 3$) (Table 2). Both sexes combined (which include undetermined individuals) showed the highest b values, and those of males were slightly higher than those of females. No significant differences were detected in these relationships among sexes ($t_{\text{obs}} < t_{\text{tab}95\%}$; $t_{\text{obs, L-W}} = 0.377$ and $t_{\text{obs, L-We}} = 0.433$).

3.3.1 Otolith structure

Based on the presence of translucent-opaque margins of the otoliths, fast growth occurred between May and August, with the highest proportion of population with opaque margin in June – July, for both years (Fig. 8). This period of fast growth corresponded with the highest values of HSI, which were attained one month later than those of Stomach Fullness (Fig. 8).

A linear relationship was observed between blue whiting TL and otolith length as follows: ($Y = 2.144 + (0.039 \cdot X)$ ($R^2=0.963$; $N=1378$, $P<0.001$), where Y = otolith length and X = blue whiting TL. The mean diameter of the first annual ring, both sexes combined, was 9.82 ± 0.74 mm (min = 7,13 mm, max = 12,1 mm), although females had larger first annual ring than males (females (mean) = 9.95 mm, CI: 0.072; males (mean) = 9.66 mm, CI: 0.075, Mann-Whitney U-test: $P<0.01$; Table S2). It is worth noting that only 25% of the measurements of the first annual ring fell below 9.4 mm. The diameter of the first annual ring and blue whiting age were not correlated (males correlation coefficient = 0.11, $P<0.05$, $N=344$; females correlation coefficient = 0.14, $P<0.05$, $N=409$).

It was possible to visualize two false rings in 80 sagitta in YOY and 1 year old individuals. The diameter of the inner false ring was 5.44 ± 0.8 mm, and that of the other false ring was 7.32 ± 0.66 mm. Considering the otolith size when these false rings were formed (i.e. the diameter of the false rings), and the fish TL-otolith size relationship established in the present work, these mean values correspond to 84 and 132 mm TL individuals, respectively.

The estimated age based on otoliths readings ranged from 0 to 8 years. Females reached older ages than males; the maximum age-class was 8 years in the case of females and 7 years in males (Table 1). The age–length key for blue whiting showed a wide range of sizes associated to each age, indicating variability in growth. The maximum variability in size at age, both sexes combined, was observed in age 1, with a size range between 15.5 cm and 30.5 cm, variability slightly decreasing the following age-classes. Overall, females showed higher variability in size at age than males (Table 1).

The lapilli daily readings indicate that juveniles were between 42 to 87 days old (Table 3), and the corresponding hatch date was between 27th of January and 13th of March. These juveniles measured between 51mm and 127 mm TL. A TL of around 90 mm was attained in the first two months.

According to the estimated VBGF parameters, blue whiting males grew faster than females ($k=0,8$ and $k=0,73$ respectively), and L_{∞} was smaller than in females ($L_{\infty}= 33$ mm TL for males and $L_{\infty} = 38$ mm TL for females) (Fig. 9, Table 4) (Hotelling, T^2 $p<0.05$). Accordingly, mean size at age was smaller in males than in females. Older individuals (age 8) were females. Differences in growth become apparent in the transition from age 1 to age 2, what is in line with the observed dominance of females from 25 cm TL. It is worth noting that most of the observed sizes at age fall below the size at age defined by the curve. Growth performance index as estimated in this study falls close to, and shifted towards higher k , the values proposed for the species in other areas, and those proposed for other gadoid species (Fig. 10).

4. Discussion

343

344 This work provides basic knowledge on the blue whiting biology in the NW
345 Mediterranean necessary for a sustainable management of its fishery. In the most recent
346 years, the total catch of blue whiting in the study area remained at very low levels. Since
347 2012 landings remained at ≤ 500 t (Generalitat de Catalunya, 2019) lower than the
348 minimum values reported by Martin et al. (2016) over a period 1961-2011, what
349 suggests that the stock would not show sign of recovery. The length of blue whiting
350 individuals captured by bottom trawl ranged between 3 and 39 cm TL, and differences
351 related with sex were found, with females reaching larger sizes than males. This
352 becomes apparent from 25 cm TL, when females were dominant in number. The size
353 range found was similar to that previously observed in the Mediterranean (García et al.,
354 1981; Macpherson and Duarte, 1991; Massutí et al., 2008; Serrat et al., 2019) and
355 smaller than that reported for the Atlantic population (Gonçalves et al., 2017; Mahe et
356 al., 2016). The minimum fished size, 3 cm TL, indicates that the recruitment to the
357 demersal habitat takes place at smaller size than previously reported in the western
358 Mediterranean, between 11.5 and 14 cm (Bas, 1964; García et al., 1981; Moranta et al.,
359 2000) and similar to that mentioned in other Mediterranean areas (Ligurian , Northern
360 Tyrrhenian and Ionian Seas) (D'Onghia et al., 2010; Mannini and Lanteri 2015; Viva et
361 al. 2015). According the daily readings, the shift from the pelagic to the demersal
362 habitat takes place at very young ages, around 40-50 days (the youngest individual
363 dated was 42 days old and measured 64 mm TL). However, 30 mm TL individuals were
364 collected during the samplings which could be younger than 42 days.

365

366 The interpretation of the blue whiting otoliths readings depends on the correct
367 identification of the first annual ring, since up to two false initial rings have been

described for this species (Bowers, 1954; Bailey, 1970; Jakupsstovu, 1979). In the present study, the diameter of the first annual ring has been defined for the NW Mediterranean (9.8 ± 0.74 mm) and confirms the values proposed by ICES (2017). Taking into account the diameter dimensions proposed for a ring to be considered as annual ring (8.33-9.33 mm; ICES 2017), 20% of our readings fell within this interval, and most of the first ring diameters were larger (77%), with 12.1 mm as the largest value. In a small number of individuals (3%) the first annual rings was below the proposed size range. Our study confirms that the two false initial rings were observed (5.44 ± 0.8 mm and 7.32 ± 0.66 mm) were below the proposed reference value for the first annual ring. The false inner ring, created when fish measured around 8 cm TL, could be related with the transition from the pelagic to the demersal environment, as suggested by Jakupsstovu (1979). In fact, this size corresponds with the most discarded size in spring (Figs. 3 and 4). A second false ring was detected in otoliths of individuals caught from October onwards. We don't have an evident explanation for the formation of this second ring, although it might reflect physiological changes.

According to the presence of the opaque margin in the otoliths analysed, in the NW Mediterranean there is one single season of fast growth, similar to that observed in the North Atlantic populations (ICES, 2017). However, this result differs from those reported for the Southern Atlantic and other Mediterranean populations for which two peaks of growth were described to take place during the year (ICES, 2017). Although this last work pointed out that the results were still preliminary, our study shows that, considering only adults specimens, there is one single season of fast growth in Mediterranean blue whiting, which allowed to validate the annual ring formation.

Our results show a high variability in the size at age for both juveniles and adults. This variability has been previously reported for the North Atlantic blue whiting and has been related with density-dependent growth, food availability and temperature (Trenkel et al., 2015). This observed variability in the size at age can also be related to the several months duration of the spawning period. In the present study, differences in growth by sex have been observed, with larger size at age and L_{∞} in females. However, males display faster growth rate (k), as previously suggested for the Atlantic, Portuguese coast and Porcupine Bank (Gonçalves, 2017), and the Mediterranean, Ionian and Ligurian Seas (Orsi Relini and Peirano 1985; Mannini and Lanteri, 2015). The estimated k values of the present work were higher, and t_0 much closer to 0, than previously reported for blue whiting in the Atlantic (Monstad et al. 1990; Bailey, 1982; Magnussen, 2007) and in the Mediterranean (Bas, 1963; Maiorano et al., 2010; Mannini and Lanteri, 2015). The daily readings of otoliths (individuals from 42 to 87 days old) allowed for a good fitting of the VBGF at the origin. Usually, this information on length at age in the first months of life when growth is faster, is not available, which would explain the differences in the growth parameters estimated in the present study and those previously reported. These differences are clearly observed in the auximetric plot (Fig. 10). Furthermore, higher k could also be related with the latitudinal distribution, since Bailey and Heath (2001) studying the larval growth showed that, along the species distribution range, k decreased northwards. The estimated theoretical size at age (VBGF) was in most cases larger than the observed sizes, especially from the age 3 (Fig 9). In this regard, it is worth mentioning that the older blue whiting (from 3 years old) are not vulnerable to bottom trawling during the second part of the year (personal observations on board). This means that the observed sizes of individuals older than 3 years mainly

correspond to those collected in the first half of the year, that is, to the youngest (and smaller sized individuals) within a given age.

Blue whiting reaches maturity when the species completes its first year of life, that is, the spawning season following its birth. This is in agreement with previous observations in the Catalan coast (Bas, 1959) and in the Adriatic (Frogliia and Gramitto 1981). This is, however, at a younger age than that reported in the Ligurian Sea, where the age at first maturity is reached during the second year of life (Orsi Relini and Peirano, 1982). In North Atlantic populations, the age at first maturity varies with latitude, from 0-2 years in the Portuguese coast (Gonçalves, 2017) to 2-4 years in the northernmost areas (ICES, 2016). The size-at-first maturity (L_{50}) observed in our study (17.7 cm TL for females and 18.3 cm TL for males) is similar to that reported for the North Tyrrhenian Sea (18.0 cm TL for females and 17.5 cm TL for males; Manninni and Lanteri, 2015), and smaller than that previously reported in the Catalan coast (L_{50} at 18.7 cm for females and 19.1 cm for males) (Serrat et al., 2019), Ligurian Sea (22cm TL) (Orsi Relini and Peirano, 1982), and the North Atlantic (between 19 and 22.5 cm TL) (Bailey, 1982; ICES 2004). These differences could be related with the discussed variability in growth, however, sampling strategies could also bias the size at first maturity. Unlike the latitudinal variation in the age at first maturity, the size at first maturity shows high variability and does not seem to have a clear pattern throughout their distribution area (Bailey, 1982).

The length-weight relationship indicates that blue whiting exhibited positive allometric growth, what would correspond with a relatively good fish condition (Froese, 2006). While this feature has been commonly described for this species (Merella et al., 1997;

Stergiou and Moutopoulos, 2001; Whilhelms, 2013), negative allometric growth has also been reported (Bailey 1982; Stergiou and Moutopoulos, 2001). Environmental differences could explain this variability, considering that the L-W relationship may vary in relation to different factors such as temperature, food (quantity, quality and size), habitat etc. (Froese, 2006; Safran, 1992). Condition factor index and HSI of blue whiting varied seasonally showing similar trends in both sampling years, reaching the best condition at the end of spring, around June, as reported by Serrat et al. (2019).

The spawning period of NW Mediterranean blue whiting takes place in winter, according to the GSI trend and the macroscopic observation of gonad maturation of females. Similar results have been reported for the Catalan coast (Serrat et al., 2019) and for other Mediterranean areas (Mannini and Lanteri, 2015). The hatch date estimated by the analysed lapilli of juveniles match with the reproductive period established in the present work, however, the number of daily readings is not enough to determine the most successful time along the whole spawning period.

Our results show that there is a close relationship between reproduction, HSI, and stomach fullness, which, in turn, have been observed to be related with growth. The reproduction takes place from November-December to March-April, with a peak in January-February, although we can not accurately date when the GSI main peak occurred because of the seasonal closure in February. According with the capital breeder strategy reported for this species (Bailey, 1982; Serrat et al., 2019), during the spawning period the feeding activity decreases and the liver supplies the energy for reproduction, resulting in an important decline of HSI throughout the spawning season. At the end of spawning period, the stomach fullness and HSI markedly increased and

the fast growth season started (around April). Later, in June-July, the HSI reached the maximum values and, practically, all individuals were in fast growth phase, as evidenced by the opaque margins observed in the otoliths. Note that during the second year, as observed in the HSI and condition factor index, the percentage of individuals in fast growth remained high until August. In August, when HSI decreased following the decline in stomach fullness, the percentage of individuals in fast growth also decreased, ending this fast growth period in October-November. From this moment, when the pre-reproductive phase begins, the stomach fullness increased allowing the recovery of lipid storage (Lambert and Dutil, 2001) as showed the increase of HSI. There is, therefore, a clear interplay between the energy invested in growth and reproduction.

When the decrease in stomach fullness takes place, at the middle-end of summer, the largest individuals become not available to bottom trawls (personal observation on board). This could suggest migratory movements, as described for NE Atlantic, even though this migratory behaviour has not been reported for the NW Mediterranean population (García et al., 1981; Martin et al., 2016). These movements could be either towards relatively higher latitudes, as occurs in the North Atlantic (Bailey, 1982; Heino et al., 2008), since the presence of larger sized individuals has been reported at the end of autumn in the upper slope of the Gulf of Lions, north of the study area (Massutí et al., 2008); or movements towards the open sea in the pelagic environment, at levels of 300-500 m depth, where the species is commonly found (Johnsen and Godø, 2007). However, both possibilities would hardly be detected with the available information. This is an interesting aspect that should be deeper studied.

According to the Scientific, Technical and Economic Committee for Fisheries (STECF, 2014), blue whiting population in the W Mediterranean (GSA 6) is highly over-exploited ($F/FMSY=9.5$), while in GSA 9 (Ligurian and North Tyrrhenian Sea) the level of overexploitation would be much lower ($F/FMSY=1.2$). Our work allowed knowing the magnitude of blue whiting discards and evidenced not only that the highest part of the catch is below the minimum landing size, 15 cm TL, in force in the Catalan coast (Generalitat de Catalunya, 2018; note that there is no minimum landing size under the Mediterranean Regulation) but also that the minimum landing size is below L_{50} in accordance with that observed in previous studies (Bailey, 1982; Serrat et al., 2019). The main reason for discarding small blue whiting is the implemented minimum landing size in the Catalan coast, and, in addition, discards do not have particular commercial interest.

Our results show that the fishery is based on ages 0-2 and that the presence of older individuals in the catch is very low. This could be a consequence of age truncation of the population due to the overexploitation, or also, might be explained by the migration of older individuals to areas outside the bottom trawl fishing grounds. When interpreting the age structure of the population, the combination of both possibilities should be considered. While the age truncation could have catastrophic consequences for the population (Longhurst, 2002), the possibility of blue whiting undertaking seasonal migrations would mean that the age truncation would be weaker than that results suggest. In any case, the large number of young and immature individuals caught negatively affect the stock status (Vasilakopoulos et al., 2011). For an exploited species with affinity to relatively cold waters in the Mediterranean, such as blue whiting, in addition to fishing, the global warming, and their synergistic effects would negatively

impact their populations (Lloret et al., 2015). Thus, it would be advisable, as suggested by Serrat et al. (2019), to increase the minimum landing size to L_{50} and to reduce the fishing pressure until the fishing mortality is below or at the proposed F_{MSY} (STECF, 2014). Fishing pressure might be reduced by the implementation of spatial closures in spring, when the highest discards rates have been observed. These measures would allow the recovering of the population making them more resilient in front of unfavorable environmental conditions (Brander, 2005).

This work provides essential information on the life history traits of blue whiting in the NW Mediterranean. Furthermore, the study fills gaps in the understanding of the interplay between food intake, energy reserves, growth and reproduction of the species. The results obtained will allow an accurate evaluation of the state of the exploited population and its trend throughout time. It is, however, necessary to go deeper in the study of the possible migration movements, and to understand the main drivers that determine the recruitment process.

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Figure captions

Figure 1. Location of the study area. The green and blue boxes correspond to the shelf edge and slope fishing grounds, respectively. The isobaths shown are 50, 100, 200, 400 and 1000 m.

Figure 2. a) Blue whiting sagitta from a Young of the Year specimen of 13.9 cm TL, captured on October 2017; the otolith size (OS) and the diameter of the two false annual rings (FAR1 and FAR2) are shown. b) Blue whiting sagitta from a 2 years old adult of 25.5 cm TL; the translucent bands (white arrows) and the distance of the first annual ring (1st AR) are shown. c) Blue whiting lapilli of an individual of 7.3 cm TL partially polished showing the primordia and the daily rings.

Figure 3. Blue whiting monthly commercial and discarded catch of port of Roses (mean resulting from the two-year sampling).

Figure 4. Blue whiting length frequency distribution of the total catch (a) in the fishing port of Roses (mean distribution resulting from the two-year sampling). Arrows indicate the minimum landing size (15 cm TL) set by the Autonomous Government of Catalonia, and the size-at-first maturity (around 18 cm TL, for both males and females, obtained in this study). b) Blue whiting length frequency distribution of the commercial catch.

766

767 **Figure 5.** Blue whiting sex ratio expressed as percentage of females in relation to the
768 total number of males and females, by size (TL in cm).

769

770 **Figure 6.** Monthly variation of the maturity stage. Only individuals above the size at
771 first maturity were represented. “Quiescent” category includes resting and immature
772 individuals above the size at first maturity.

773

774 **Figure 7.** Monthly variation of the mean Gonadosomatic Index, mean Hepatosomatic
775 Index, and mean Le Cren Condition Factor with their respective standard error bars.

776

777 **Figure 8.** Monthly variation of Hepatosomatic Index (black dots); Stomach Fullness
778 (blue dots); Otolith edge condition (bars) indicating the proportion of the population
779 with opaque margin otoliths (grey) and translucent margin otoliths (white), that
780 correspond to fast and slow growth, respectively.

781

782 **Figure 9.** Blue whiting Von Bertalanffy Growth Curve (VBGC) for combined sexes
783 (black), females (red) and males (blue). Dots correspond to the otoliths that were
784 examined for the determination of age.

785

786 **Figure 10.** Auximetric plot for blue whiting and other Gadidae species that allows
787 comparison between L_{∞} and k estimated in this study (black) with other estimates
788 obtained for blue whiting (red) and other Gadidae (green). Note that while L_{∞} falls
789 within the ranges of previous estimates of this parameter, k is the highest among the
790 available estimates for the species. Source: Froese and Pauly (2019).

Table 1

Table 1. Age-length key for combined sexes, females and males based on otoliths readings of Mediterranean blue whiting. Classe age 0 includes the YOY and juveniles dated from daily increments.

Age (years)	Combined sexes										Total
	0	1	2	3	4	5	6	7	8		
Total Length (cm)	DAILY	YOY									
5-5.9	1									1	
6-6.9	8									8	
7-7.9	14									14	
8-8.9	13									13	
9-9.9	5									5	
10-10.9	5									5	
11-11.9	1									1	
12-12.9	1									1	
13-13.9		10								10	
14-14.9		39								39	
15-15.9		56	1							57	
16-16.9		73	10							83	
17-17.9		83	17							100	
18-18.9		73	23							96	
19-19.9		65	30							95	
20-20.9		42	41							83	
21-21.9		37	55							92	
22-22.9		21	71	3						95	
23-23.9		7	81	3						91	
24-24.9		1	73	16	1					91	
25-25.9			66	28	2					96	
26-26.9			49	36	8					93	
27-27.9			24	45	10	1				80	
28-28.9			12	34	9	7	4			66	
29-29.9			3	23	10	12	6			54	
30-30.9			1	8	19	10	6	2	1	47	
31-31.9				4	9	10	6	3	1	33	
32-32.9					4	8	3	4		19	
33-33.9						5	4			9	
34-34.9						2	2	2	1	8	
35-35.9							3			3	
36-36.9							1	3		5	
37-37.9							1			2	
38-38.9								1		1	
39-39.9									1	1	
Total	48	507	557	200	72	55	36	14	4	4	1497
%	3.2	33.9	37.2	13.4	4.8	3.7	2.4	0.9	0.3	0.3	100
Mean length at age (cm)	8.3	18.0	23.1	27.2	29.2	30.8	31.8	33.1	33.8	37.1	22.4
SD	1.5	2.3	2.8	1.8	1.9	1.7	2.4	2.2	3.5	2.1	5.5

	Females										Males									
	0 YOY	1	2	3	4	5	6	7	8	Total	0 YOY	1	2	3	4	5	6	7	8	Total
50-59																				
60-69																				
70-79																				
80-89																				
90-99																				
100-109																				
110-119																				
120-129																				
130-139	5									5	5									5
140-149	17									17	22									22
150-159	27									27	26	1								27
160-169	34	5								39	36	5								41
170-179	42	6								48	40	11								51
180-189	35	10								45	38	13								51
190-199	34	12								46	31	18								49
200-209	24	17								41	15	24								39
210-219	23	23								46	14	32								46
220-229	12	29								41	9	42	3							54
230-239	7	35	2							44		46	1							47
240-249	1	40	2	1						44		33	14							47
250-259		41	10							51		25	18	2						45
260-269		32	19	1						52		17	17	7						41
270-279		20	25	2						47		4	20	8	1					33
280-289		12	28	4	1					45			6	5	6	4				21
290-299		3	19	8		1				31			4	2	12	5				23
300-309		1	8	19	8		1			37					2	6	1	1		10
310-319			4	9	9	2				24					1	4	3	1		9
320-329				4	7	3				14					1		4			5
330-339					5	4				9								1		1
340-349					2	2	2		1	7								1		1
350-359						3				3										
360-369						1	3		1	5										
370-379						1			1	2										
380-389								1		1										
390-400									1	1										
N	261	286	117	48	32	17	6	1	4	772	236	271	83	24	23	19	8	4		668
%	33.8	37.0	15.2	6.2	4.1	2.2	0.8	0.1	0.5	100.0	35.3	40.6	12.4	3.6	3.4	2.8	1.2	0.6		100.0
Mean																				
Length	182.6	237.3	278.9	301.3	318.5	337.5	347.7	386.0	370.5	226.9	177.5	224.2	262.0	272.9	293.2	300.3	317.6	322.3		
SD	24.0	28.8	16.9	14.7	13.0	19.5	23.7	-	21.2	62.9	21.6	25.3	15.3	10.8	11.2	11.3	8.3	17.4		

Table 2. Blue whiting parameters of the length-weight relationship, for both sexes combined, females and males (L= Total Length, W= Total Weight, We= Eviscerated Weight)

	L-W			L-We		
	Combined	Females	Males	Combined	Females	Males
a	0.0038	0.0053	0.0045	0.0031	0.0066	0.0043
b	3.187	3.083	3.137	3.232	3.071	3.125
R ²	0.991	0.978	0.976	0.992	0.982	0.983
n	3876	1415	1346	3464	1415	1346

Table 3

Table 3. Age-length Key based on the readings of the daily growth increments of lapilli otoliths from Mediterranean blue whiting juveniles.

Age (days)	42-51	52-61	62-71	72-81	82-91	No	Mean age (days)	SD
TL (mm)								
51-60		1				1	57.0	
61-70	5	3				8	49.4	5.1
71-80	7	10				17	51.7	4.5
81-90	1	3	7			11	60.9	6.9
91-100			4			4	64.5	2.4
101-110			2	3		5	72.2	5.0
111-120					1	1	87.0	
121-130			1			1	70.0	
N	13	17	14	3	1	48	57.9	9.9
Mean TL (mm)	72.3	74.5	95.3	103.0	115.0	83.3		
SD	6.5	8.6	11.9	2.6		15.6		

Table 4. Blue whiting parameters of the Von Bertalanffy growth curve (VBGC) and their SE, and growth performance index ($\phi = \log_{10}k + 2\log_{10}L_{inf}$) for combined sexes, females and males.

	Linf		<i>k</i>		t0		ϕ
Combined	370	3.77	0.71	0.03	-0.25	0.031	4.99
Females	380	4.89	0.73	0.03	-0.2	0.028	5.02
Males	330	3.86	0.8	0.04	-0.29	0.034	4.94

Figure 1
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Figure 2
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Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

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Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: