



Reproduction and Sexual Maturity of European Sardine (*Sardina pilchardus*) in the Central Mediterranean Sea

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Understanding drivers of fish maturity is essential to predict the productivity, stability, and resiliency of exploited populations. Size at maturity for European sardine (*Sardina pilchardus*) in the Central Mediterranean Sea has never been published within rigorous peer review process. In the past, stock assessment working groups in the Mediterranean requested such information; however, the size at which 50% of the fish population reaches the sexual maturity (L_{50}) often received weak estimates based on a single or few years of observation, which do not necessarily reflect the whole stock. To address this data gap for the Central Mediterranean Sea, the present research estimated size at maturity of European sardine in the Strait of Sicily. In the study period (2009–2017), sampled individuals exhibited significant differences in size range as well as in body condition and reproductive effort. Data also permitted a clear identification of the spawning season, starting in September–October and ending in March–April the following year. Along the analyzed period, the size at first maturity ranged from 108 to 124 mm (total length) for females and from 102 to 122 mm for males. Significant differences were recorded among genders and years. Moreover, a goodness-of-fit measure was proposed to assess the robustness and reliability of L_{50} estimates, and thus selecting those that minimize the fitting-associated errors. Finally, results suggested that the low proportion of immature individuals in the samples represents the main source of bias in L_{50} estimation and possible solution was also proposed.

Keywords: size at first maturity, gonadosomatic index, condition factor, Strait of Sicily, spawning season and peak

INTRODUCTION

Small pelagic species comprise about one quarter of the global catch of fishes, such that they are both economically and ecologically considerable (Leonart and Maynou, 2003; Ganas, 2014). Among these species, the European sardine, *Sardina pilchardus* (Walbaum, 1792), plays a key role in maintaining ecological processes in marine systems, occupying an essential intermediate trophic level in pelagic ecosystems (Bakun, 2006; Rumolo et al., 2016). European sardine (ES) belongs to the Clupeidae family, inhabiting from the North Sea to Senegal in the Atlantic waters, as well as in the

Mediterranean Sea (Parrish et al., 1989). ES is a schooling fish, usually inhabiting the continental shelf (Iglesias et al., 2003; D'Elia et al., 2014), whose landings account for 15% (more than 185,000 tons) of the total production of the Mediterranean Sea between 2016 and 2018 (FAO, 2020). ES is a multiple batch spawner with continuous development of gametes, showing a protracted spawning period with early maturation and high fecundity across most of the distribution range (Zwolinski et al., 2001; Somarakis et al., 2004; Silva et al., 2006; Sinovčić et al., 2008; Ganas, 2009), also displaying a high variability in terms of its recruitment, biomass, and distribution, mostly dependent on environmental and climatic conditions (Lluch-Belda et al., 1989; Schwartzlose et al., 1999; Ganas, 2009; Katara et al., 2011; Bonanno et al., 2016). Moreover, as a likely income breeder (i.e., animals for which energy intake for reproduction depends on feeding during the spawning season), environmental variability may determine the inter-annual variability of size at maturity by the availability of feeding resources (McBride et al., 2015). Unfortunately, this species, as other short-living fishes, displays fast growth, which can largely impact the maturation schedule according to stored energy and the way the energy is allocated between growth and reproduction, prior and along the spawning season (McBride et al., 2015). Variation in size- and age-at-maturity has a direct implication on productivity fluctuations in many fish populations, with implications for fisheries management (Morgan, 2018). For these reasons, a yearly-based evaluation of these populations is carried out routinely by stock assessment working groups within Mediterranean, Black Sea, and Atlantic waters [General Fishery Commission for the Mediterranean and Black Sea (GFCM); International Council for the Exploration of the Sea (ICES)].

Life history parameters, and particularly reproductive traits, are the basis for assessing population productivity and resilience, making them basic information for stock management. The estimate of the length at which 50% of the population appears sexually mature (L_{50}) is mainly used to define the minimum landing legal size for the exploited populations, although the L_{50} diverges to the minimum size at maturity, also in species maturing early (old age 0 and young age 1) like sardine (Amenzoui et al., 2006; Sinovčić et al., 2008).

Despite the relevance of this resource (ICES, 2019; SAC, 2019), only a few studies focused on length at maturity of ES population in the Mediterranean Sea, namely in the eastern Iberian waters (Silva et al., 2006) and in the Aegean waters (Tsikliras and Koutrakis, 2013). In the central Mediterranean waters only a study from North Adriatic Sea is available in the literature (Sinovčić et al., 2008). However, old parameters may no longer be appropriate given the likelihood that life history traits are adaptive and may change in response to changing environmental conditions or to evolutionary responses (Kjesbu and Witthames, 2007; Gordo et al., 2008; McBride et al., 2013; Ganas et al., 2015). Among others, gonad maturation and extension of reproductive season depend on both the genetic features and environmental influences, as geographic and/or reproductive isolation, temperature, and food availability (Begg et al., 2005; Sinovčić et al., 2008). Fishes displayed the ability to grow and mature at smaller sizes

at low latitudes than the same species at higher latitudes, suggesting fish ability to adapt to wide patterns of environmental conditions (Ferreri et al., 2019). Furthermore, in the over-exploited stocks a decrease in size and age at maturity was observed, highlighting the importance of these estimates as potential indicators for the effects of fisheries (Olsen et al., 2004; Lappalainen et al., 2016). New or improved estimates of maturity ogives should assist with sustainable management of living marine resources in both data-poor and data-rich situations.

In the above-mentioned context, the present study using a 9-years-long time series obtained within the European Data Collection Framework (DCF; EC 665/2008) provided basic knowledge on the reproductive biology and its seasonal variability for the ES in the Central Mediterranean Sea. Moreover, length at sexual maturity of the sardine stock was estimated for each year and gender, to provide valid reference points for the assessment models as well as for the definition of management measures, as the minimum legal landing size.

MATERIALS AND METHODS

Sampling

Sardine in Geographical Sub-Area 16 [GSA 16, i.e., the Strait of Sicily, defined according to the Mediterranean sub-areas adopted for stock assessments by the GFCM (2009)] are targeted by purse seine and mid-water pelagic trawls. The sampling is of a stratified nature in that the fishing vessels of the fleet are divided into homogenous groups, based on four stratification variables (landings, length classes, geographical subregions, fleet segments), and independent samples are taken from each of these clusters. The advantage of using two different fishing techniques allowed to obtain both a wider size range of samples and a wider spatial coverage of the distribution ground of this species. Moreover, the movement behavior of the purse seine fleet along the year allows to retrieve more offshore samples than the other mid-water coastal trawling (Basilone et al., 2004). Most of the fishing activities are concentrated in the central part of the study area (**Figure 1**), where larger part of the population is located (Barra et al., 2015; Bonanno et al., 2015). During autumn and winter, the fully recruited sardine population is known to show migratory behavior for spawning purposes (Morello and Arneri, 2009; Ganas and Nunes, 2011). This expansion most likely reflects the peculiarities of the Mediterranean Sea, where suitable areas favoring growth, feeding, and spawning processes for small pelagic populations tend to be localized (Basilone et al., 2017). The existence of such limited suitable areas along with complex oceanographic and topographic characteristics (i.e., irregularities in the coastline and the bathymetry) is likely to prevent long-distance migration for sardine between spawning and juvenile grounds (Giannoulaki et al., 2011). This is even more pronounced in the Strait of Sicily, where no significant seasonal variation was shown (Barra et al., 2015). Therefore biological sampling from coastal (mid-water trawling covered) to more offshore waters (purse seining covered) could be considered representative of most part of the population, including the

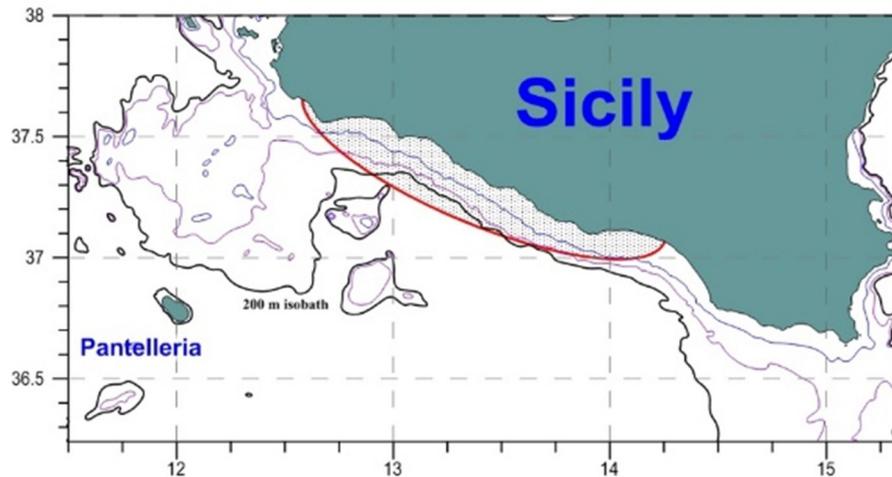


FIGURE 1 | Map of the study area with the main fishing ground located in the shadowed sector, according to Basilone et al. (2004). Isobaths of 50 m, 100 m, and 200 m (black line).

most spawning fraction in winter (Ganias et al., 2007). Along 9 years (2009–2017), monthly random samples of ES were collected from commercial landings in the Strait of Sicily area (Figure 1).

At the laboratory, individuals were sexed and analyzed for total body length (TL) to nearest 1 mm, total weight (TW) somatic weight (i.e., the gonad-free body weight; SW) to nearest 0.1 g, and gonadic weight (GW) to nearest 0.01 g. Along 9 years, a total amount of 14916 ES was sexed (7221 females and 7195 males) and reproductive information collected. Monthly samples ranged between a minimum of 354 in January to 3266 in September (Table 1) and the number of monthly samples varied among years, but January appears the most-often under-sampled month. However, the total amount of sampled fish showed a relevant decrease only in 2016 and 2017. No use of live animals has been required for this study and no specific permissions were needed for the sampling activities in all of the investigated areas, because the target species is commercially harvested (neither endangered nor protected) and it was caught in areas where fishing is allowed.

Gonad maturity was macroscopically determined, and development stages were assigned by means of a six-class scale for the identification of reproductive phase. This scale, proposed by the international scientific community within the context of the ICES, is particularly developed for sardine and anchovy, that is, small pelagic species with asynchronous gonad development and indeterminate fecundity (ICES, 2008). According to the agreed international protocol (ICES, 2008), the six phases are: (1) immature; (2) developing; (3) imminent spawning; (4) spawning; (5) partial post-spawning; and (6) spent. Phase 1 was considered immature (spawning not imminent this year) and phases 2–6 were considered mature (they have contributed or are contributing to the reproduction of the year).

Reproduction

Many studies have employed condition indices to understand fish population health and variability (Lloret et al., 2012; Thorson, 2015; Brosset et al., 2017). Body condition is a way to measure the amount of stored energy in the body and reflects a set of biotic (e.g., food availability, parasitic infections, physiology) and abiotic (e.g., physical conditions) factors experienced by individuals over a period of their life (Vila-Gispert and Moreno-Amich, 2001; Lloret et al., 2002).

In order to evaluate the existence of differences in body size between genders, an ANCOVA test was carried out on log-transformed data of TL and SW ($F = 98.36$; $p < 0.001$). According to these results, all the following analyses were carried out for separated genders.

The relative somatic condition factor (K_n) of individuals was estimated as follows (Le Cren, 1951):

$$K_n = \frac{SW}{aTL^b}$$

where a and b are the parameters of the length–weight regression (i.e., TL vs. SW), SW is the somatic weight (g), and TL is the total fish length (mm). Somatic, rather than total, weight is used to avoid variability due to the maturity stage. For K_n computation the length–weight regression power model coefficients were estimated for each gender separately: $a = 0.0042$ and $b = 3.2237$ ($r^2 = 0.89$) for females, and $a = 0.0025$ and $b = 3.4105$ ($r^2 = 0.8557$) for males.

Energy allocated to reproductive growth (i.e., reproductive investment) was estimated by the gonadosomatic index (GSI):

$$GSI = GW/SW * 100$$

where GW is gonadic weight (g) and SW is somatic weight (g) (DeVlaming et al., 1982).

TABLE 1 | Number of European sardine sampled (*n*) for each gender (i.e., female [F] and male [M]) along the study period, by year and month.

Year	Gender	n/size range	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total		
2009	F	n		83	118	116		317			436	69	151		1290		
		Min		114	128	130		122			115	148	125				
		Max		163	175	173		165			203	198	186				
	M	n		66	180	183		218			425	45	303			1420	
		Min		108	123	122		114			114	130	119				
		Max		159	169	167		159			180	192	173				
2010	F	n			131	146	110	135			324		211	65	1122		
		Min			122	134	102	114			113		116	121			
		Max			179	177	170	160			169		180	158			
	M	n			319	148	147	66			398		215	84		1377	
		Min			117	131	121	125			114		117	117			
		Max			178	173	156	147			165		165	151			
2011	F	n	72		83	98		154			386		127		920		
		Min	120		126	125		135			123		127				
		Max	157		168	157		177			169		189				
	M	n	78		77	18		23			269		137			602	
		Min	115		129	130		138			128		122				
		Max	155		165	150		158			162		180				
2012	F	n		56	64	47	103	40	96	126	72	99	83		786		
		Min		124	121	119	121	124	103	106	127	123	142				
		Max		177	176	146	150	138	170	169	161	171	183				
	M	n		88	113	19	19	20	36	60	53	193	67			668	
		Min		114	121	119	126	126	128	125	125	117	139				
		Max		165	159	136	137	139	174	156	149	165	185				
2013	F	n			69					83	310	147	79		688		
		Min			119					133	103	127	147				
		Max			139					168	166	185	185				
	M	n			31					34	188	113	71			437	
		Min			120					136	115	128	132				
		Max			143					156	164	173	173				
2014	F	n		2	5		58	53	174		94	71	179	163	799		
		Min		158	142		129	103	115		120	147	127	123			
		Max		178	154		157	159	166		162	179	174	180			
	M	n		12	23		53	63	99		73	79	264	100		766	
		Min		135	130		124	135	125		124	142	121	122			
		Max		153	150		151	154	160		155	173	175	168			
2015	F	n		38	209	90	303	220	101	151	89	111	60	144	1516		
		Min		117	114	133	107	110	119	108	125	92	110	101			
		Max		162	158	174	151	152	148	147	166	177	181	183			
	M	n		112	183	107	213	103	35	45	87	114	103	201		1303	
		Min		114	112	134	116	117	120	111	133	110	110	109			
		Max		160	158	163	149	143	140	156	159	164	167	170			
2016	F	n	62		39	31	38	34	64	29	41				338		
		Min	107		123	126	127	122	122	118	112						
		Max	170		152	157	155	156	152	170	155						
	M	n	142		17	18	17	26	44	22	22					308	
		Min	105		118	124	124	121	121	120	114						
		Max	160		151	154	147	151	155	160	143						
2017	F	n		23	32	31	46						97	33	262		
		Min		123	119	129	117							115		115	
		Max		148	153	157	156							165		160	
	M	n		25	24	21	60							140		44	314
		Min		120	120	130	119							105		105	
		Max		142	148	151	147							165		145	

The minimum (Min) and maximum (Max) total length (mm) were also provided to evaluate the size range for each subset.

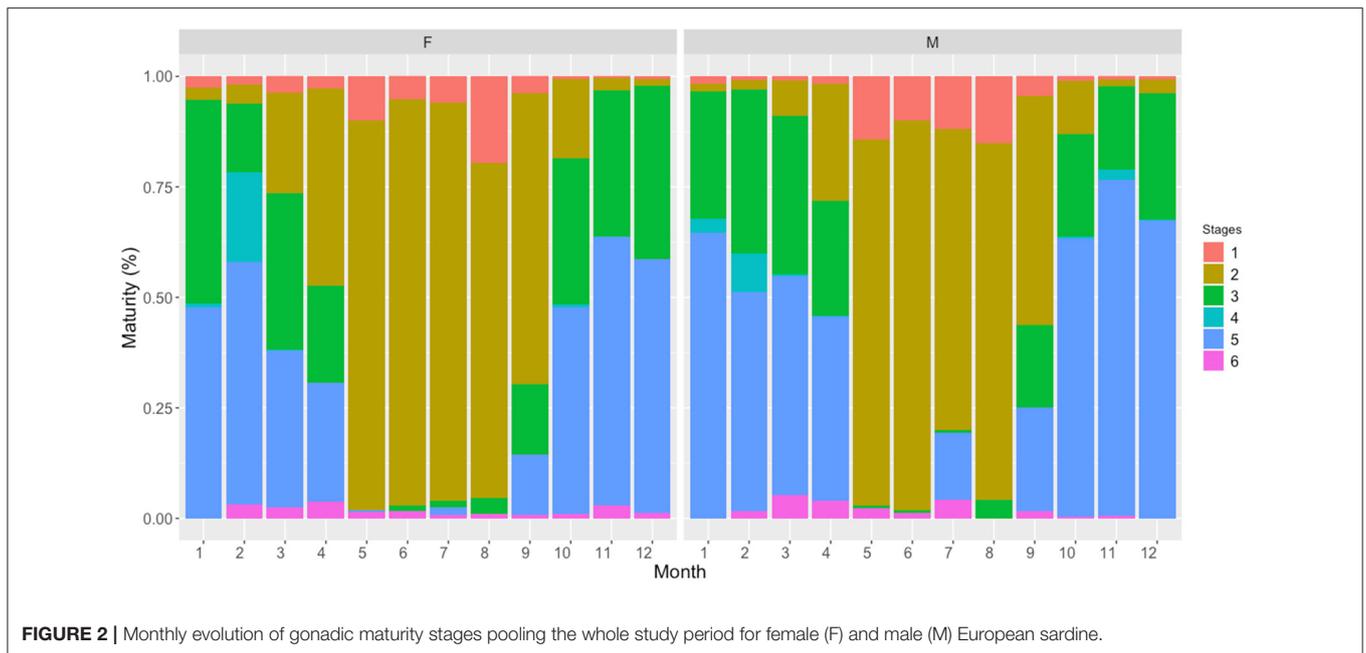


FIGURE 2 | Monthly evolution of gonadic maturity stages pooling the whole study period for female (F) and male (M) European sardine.

A logistic model was applied to fit size at maturity data for estimating the length at which the 50% of the population appears sexually mature (L_{50}), as indicated by the inflection point of the ogive. Fitted data belong to the spawning season (September–March; see Results section for more details) of sardine as determined by the gonadosomatic and condition indices monthly evolution:

$$P_i = (1 + e^{-(\alpha + \beta x_i)})^{-1}$$

where, P_i is the probability of being mature at size x_i , and α and β are model parameters representing the intercept and slope of a linear form of this model; then, based on estimated parameters, L_{50} is computed as: $L_{50} = -\alpha/\beta$.

To investigate the existence of differences in L_{50} between genders, the ogives were computed per separate genders but the analyses were carried out also by pooling males and females together by year, to evaluate if increasing the number of observations would benefit to the goodness of fitting.

Although there is no commonly accepted agreement on how to assess the fit of a logistic regression, there are some approaches. The goodness of fit of the logistic regression model can be expressed by some variants of pseudo- r -squared statistics (*Pseudo- r^2*), most of which being based on the deviance of the model (Ferreri et al., 2016). Therefore, in order to compare the goodness of fit among obtained maturity ogives, the McFadden's r^2 , based on the log-likelihood kernels for the intercept-only model and the full estimated model has been adopted (McFadden, 1974). Furthermore, the graphical representation of ogive fitting with their confidence curves and the bins of mature/immature individuals plotted along the axis allowed more detailed evaluation of each fitting ogive.

The analyses were performed in the R statistical environment (R Core Team, 2018), using the “sizeMat” package for maturity ogive estimates (Torrejon-Magallanes, 2020). Area-specific maturity ogives are presented with 95% confidence intervals for the predicted probability, which were determined by bootstrapping 1,000 times (see Ferreri et al., 2019, for more details).

RESULTS

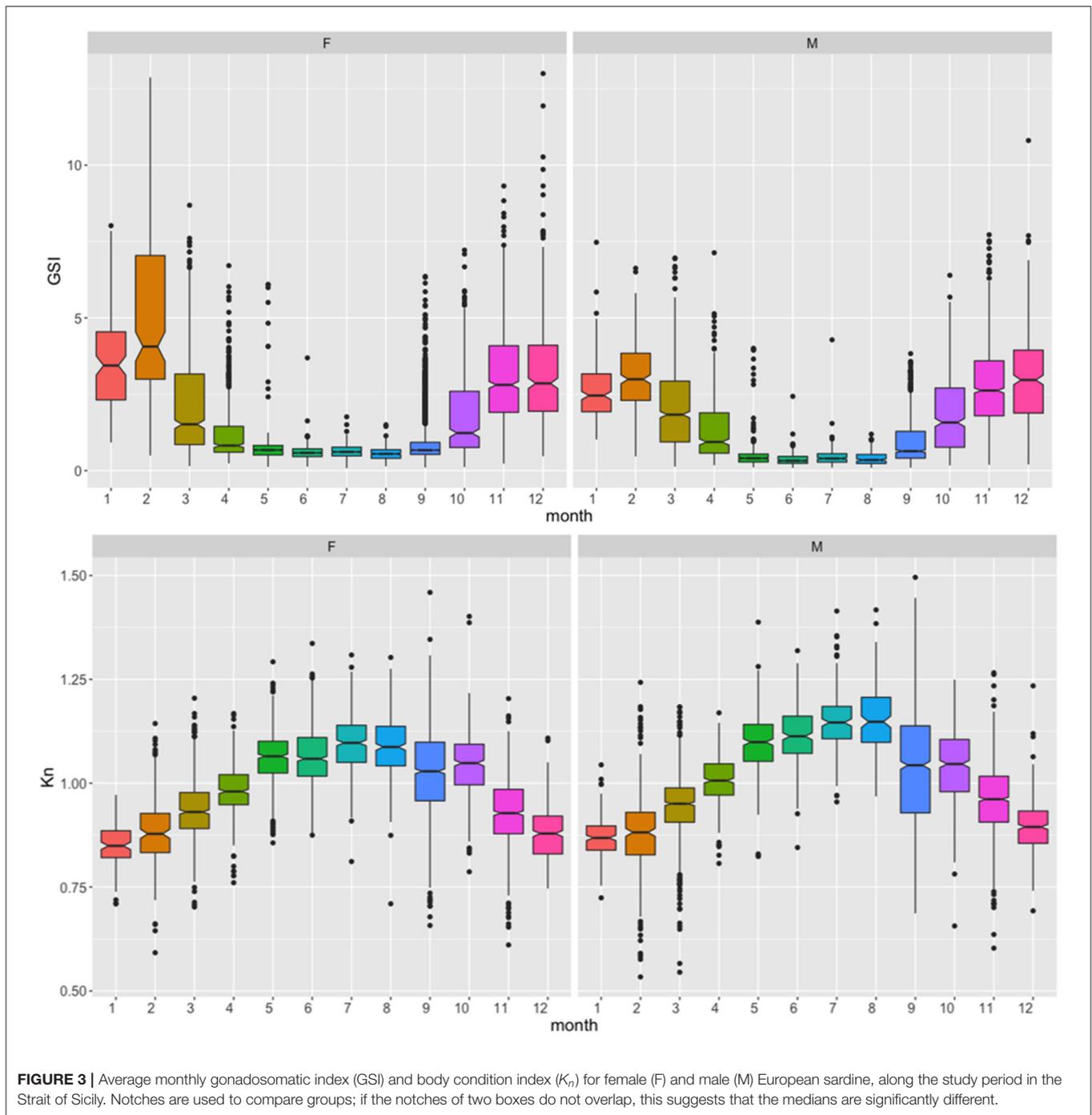
Reproductive Cycle and Body Conditions

The monthly proportion of mature stages along the year showed that stage 2 individuals (developing oocytes, which will be spawned within the year) mainly dominated the samples between May and September, while most advanced maturity stages (3–6) were concentrated mainly from October to April (Figure 2). Moreover, the pattern in spawning seasonality was similar between genders, further supporting the period between October and March/April as the spawning period for both genders.

Monthly GSI, based on the pooled data along the whole study period, confirmed a 7-month spawning season extension, between September and March, as also supported by the lower K_n along these months (Figure 3). Although both genders displayed a similar pattern, the monthly GSI showed higher average values in females, especially during the spawning peak (January–February).

Length at Maturity

The L_{50} estimations were obtained by selecting data from the spawning period as determined by reproductive indices and maturity monthly patterns (September–March), separately for gender and year together with an r^2 statistic to evaluate the goodness of fit. Along the study period, L_{50} estimations were



higher in females, with values ranging between 114 (± 1.1) mm and 126 (± 0.8) mm, than in males, L_{50} between 102 (± 5.7) mm and 122 (± 1.4) mm, the latter displaying wider confidence intervals and reduced *Pseudo-r*² values (Table 2). Confidence intervals denoted significant differences between females and males almost over the whole period (Figure 4).

However, within each gender, the L_{50} estimations showed very similar values along most part of the study period (Figure 4). In females, L_{50} values could be split into two groups: the higher

between 121 and 126 mm (2009, 2012, 2013, 2014, 2016) and the lower between 114 mm and 117 mm (2010, 2011, 2015, 2017); while in males the two L_{50} groups were less evident than in females, since the wider confidence intervals make the separation difficult, particularly in 2011 and 2016 (Figure 5).

In females, the higher *Pseudo-r*² values identified the best model fitting for most of the sampling years (2009, 2012–2014, and 2016), which showed also the higher L_{50} values; while non-optimal fittings were advisable in 2011 and 2017 (Table 2). The

TABLE 2 | Length at maturity (L_{50}) estimations for separated genders, for each year.

Year	Females L_{50} (CI) (mm)	Intercept	Slope	$Ps-r^2$	Males L_{50} (CI) (mm)	Intercept	Slope	$Ps-r^2$	Overall L_{50} (CI) (mm)	Intercept	Slope	$Ps-r^2$
2009	121 (0.7)	-38.86	0.32	0.52	112 (2.3)	-13.70	0.12	0.15	117 (1.0)	-20.04	0.17	0.26
2010	117 (1.0)	-39.67	0.33	0.35	110 (2.1)	-23.04	0.20	0.18	113 (1.1)	-24.79	0.21	0.22
2011	115 (3.3)	-19.32	0.16	0.25	107 (5.7)	-14.63	0.13	0.17	119 (2.0)	-10.52	0.08	0.10
2012	121 (1.8)	-35.52	0.29	0.46	114 (3.0)	-29.09	0.25	0.34	126 (0.5)	-27.76	0.22	0.39
2013	124 (0.5)	-44.43	0.36	0.59	122 (1.4)	-32.82	0.26	0.40	130 (0.4)	-27.30	0.20	0.46
2014	126 (0.8)	-59.43	0.47	0.62	117 (2.6)	-27.80	0.24	0.34	138 (0.5)	-15.12	0.11	0.17
2015	114 (1.1)	-28.53	0.25	0.46	108 (2.0)	-14.76	0.14	0.22	114 (0.9)	-14.93	0.13	0.25
2016	123 (1.6)	-19.03	0.15	0.39	102 (5.7)	-7.41	0.07	0.11	115 (2.0)	-10.17	0.08	0.17
2017	117 (3.8)	-11.97	0.10	0.14	110 (3.8)	-8.56	0.07	0.11	112 (2.8)	-9.26	0.08	0.12

Ogive model fitting parameters estimates were also provided with their confidence intervals within brackets as well as the Pseudo- r^2 ($Ps-r^2$) as a measure of goodness of fit (Flores et al., 2019).

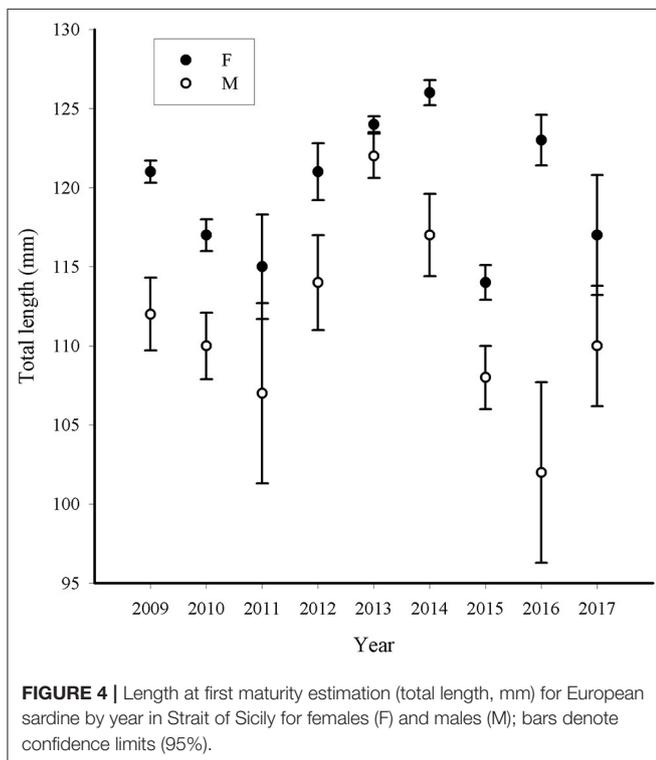


FIGURE 4 | Length at first maturity estimation (total length, mm) for European sardine by year in Strait of Sicily for females (F) and males (M); bars denote confidence limits (95%).

$Pseudo-r^2$ values were generally lower in males than in females and particularly in 2016 and 2017, but also the period 2009–2011 displayed estimates below 0.20 value (Table 2). In males, the analyses that minimize error and improve fitting (i.e., with higher $Pseudo-r^2$ values) were obtained between 2012 and 2014, with L_{50} ranging between 117 mm and 122 mm (Table 2). The $Pseudo-r^2$ values for ogives of pooled genders presented lower values than those for females, but better than $Pseudo-r^2$ on males except in 2011 and 2017 (Table 2).

The visual inspection of ogive graphs displayed thinner confidence intervals for combined genders than separated ones (Figure 5), although the pooled genders not always increased the goodness of fitting, as indicated by the $Pseudo-r^2$ (Table 2).

However, the ogive plots highlighted that years with wider confidence intervals were linked to the poor number of immature specimens, especially in the lower size classes (Figure 5). Finally, a plot of $Pseudo-r^2$ vs. L_{50} was provided to identify the best L_{50} estimation among years (Figure 6, left panel). This plot showed the length at maturity separately estimated per each year and gender have major accuracy and precision (Figure 6). Such a plot highlights how fittings of maturity ogive improved reaching more robust estimation at values of L_{50} around 125 mm ($Pseudo-r^2 > 0.5$) (Figure 6, left panel).

DISCUSSION

In multiple-spawning fishes, specifically those with asynchronous gonadic development, such as sardine, macroscopic determination of spawning phase is difficult without the support of microscopic examination; this is due to its subjectivity and variability, which represent a source of bias particularly relevant in discriminating immature from mature individuals (Costa, 2009; Ferreri et al., 2009; Khoufi et al., 2014). Nonetheless, macroscopic evaluation of gonads is widely adopted in the fishery resources assessment, because it allows examining a wider number of fishes (Ferreri et al., 2009; Basilone et al., 2015). Achieving a wide range of immature and mature sizes can also be an obstacle when data only came from commercial fisheries (Bromley, 2003), particularly for small fishes that may reach the recruitment size to fishery at about the same length than first maturity. To reduce this important source of bias, the ogive model may be also fitted by pooling the data sets of both genders, particularly when used for assessment purposes (ICES, 2010).

The estimation of the spawning seasonality from somatic and gonadic condition indices agrees with observations of monthly maturity status further supporting the timing and duration of ES spawning in the Strait of Sicily, which occurred from September to March the following year, in agreement with past studies across the Mediterranean (Tsikliras et al., 2010). Despite its wide use, the validity of GSI has often been questioned because of the possible ovarian growth allometry, and it has generally been recommended that this index should not be used without proper validation (DeVlaming

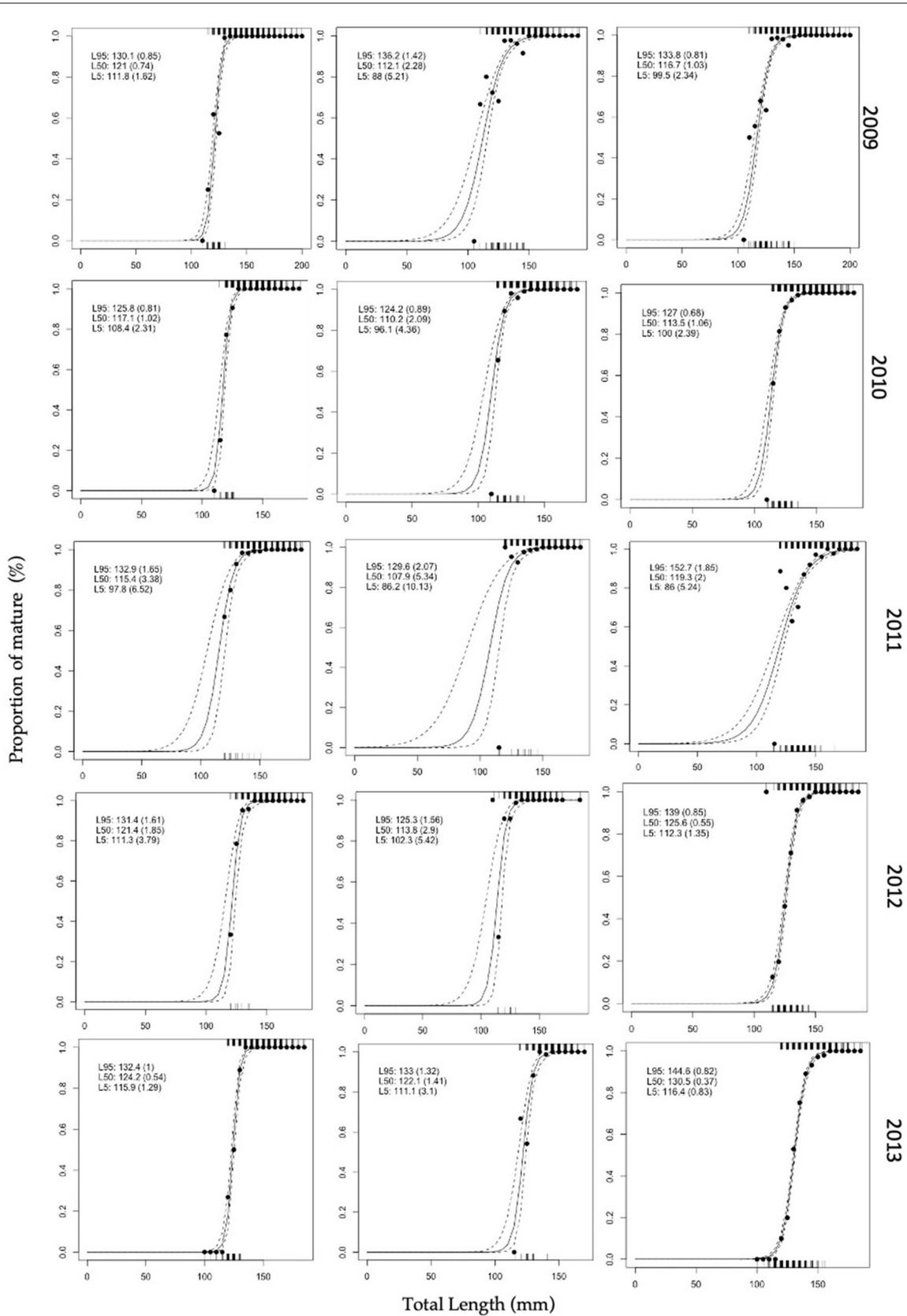


FIGURE 5 | Continued

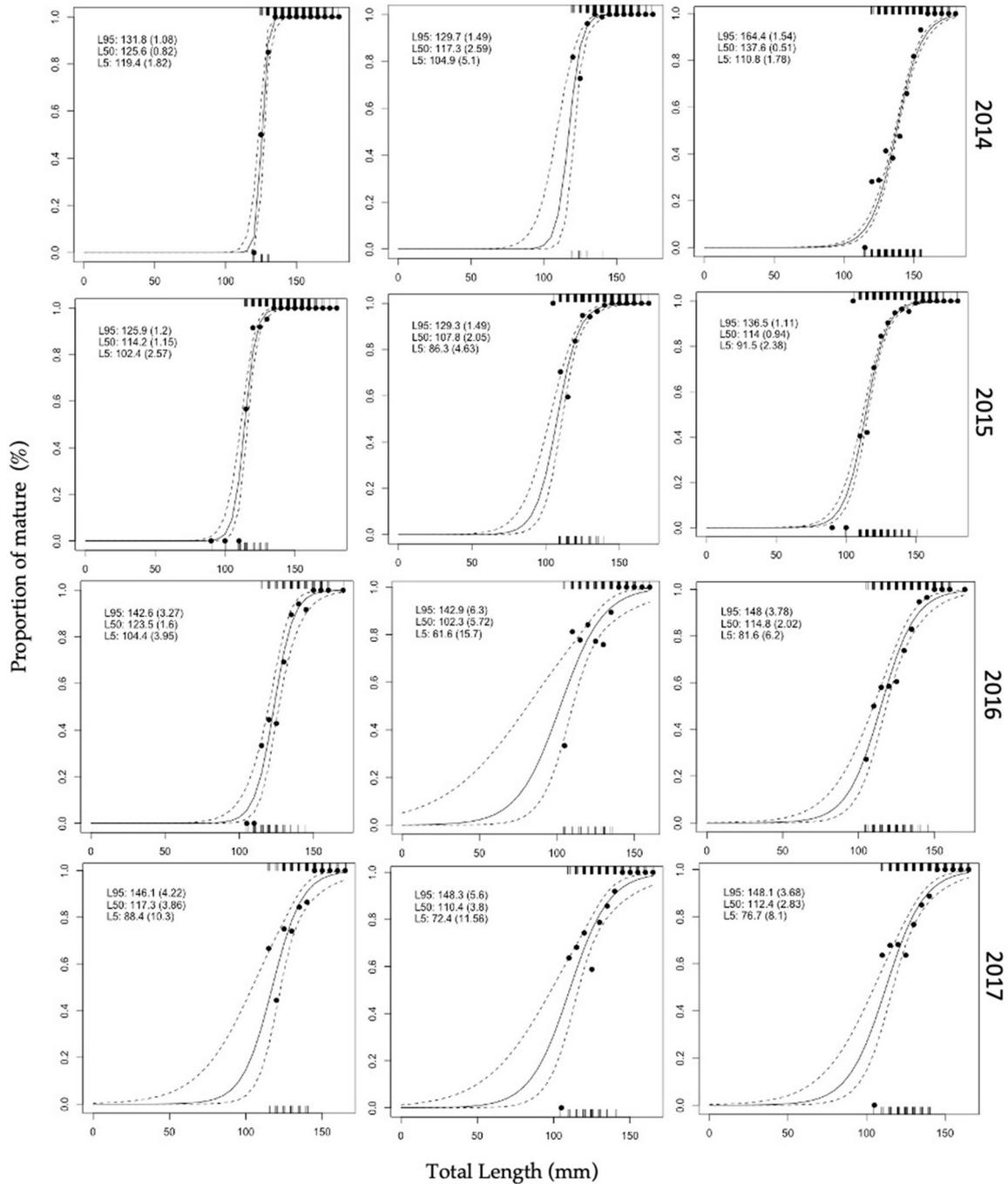
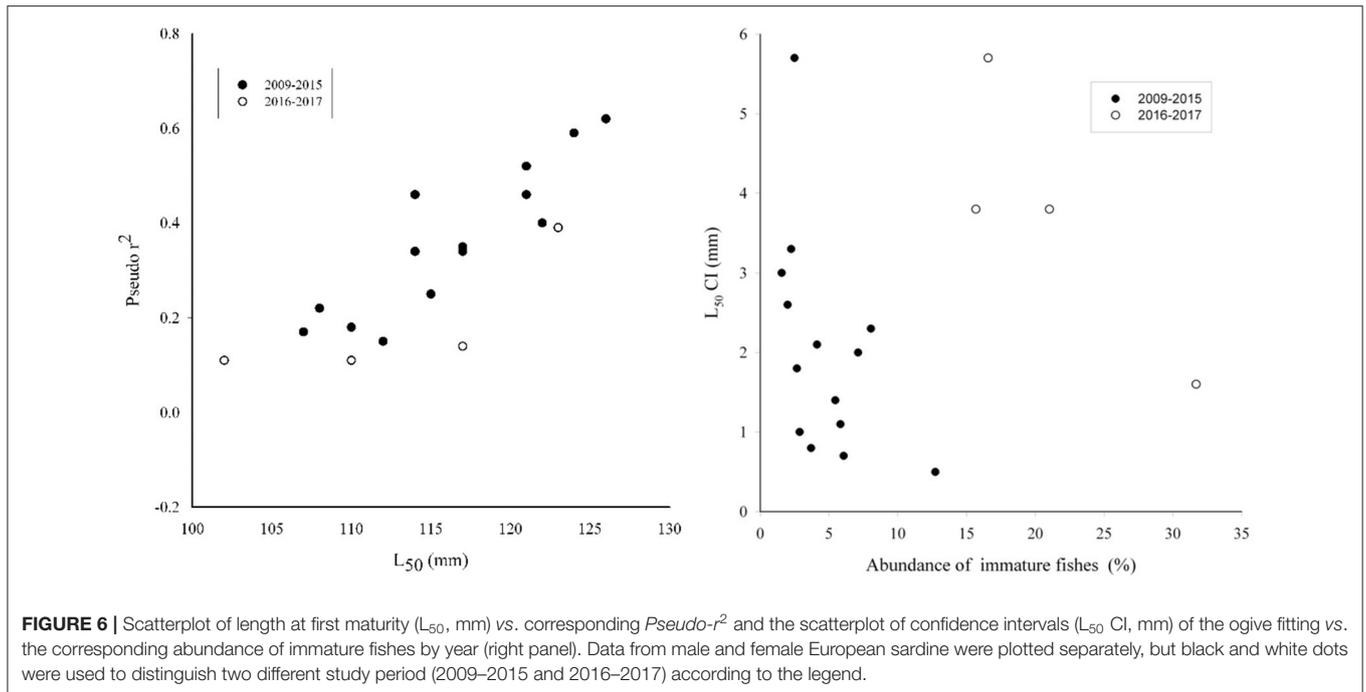


FIGURE 5 | Maturity ogives for European sardine in the Strait of Sicily per year, from 2009 to 2017 for females (left panels) males (middle panels) and overall (right panels). Solid line is the predicted proportions of mature ES at length, the dashed lines denote the 95% confidence curves, and the tick marks on the bottom and top axes indicate the immature and mature ES recorded, respectively. The proportion of mature for each bin is also reported (black, filled circles). The point estimates for mean size (+95% CL) are also provided for 5% (L₅), 50% (L₅₀), and 95% (L₉₅) mature individuals. See **Table 2** for more details about the logistic equation parameters for each year.

et al., 1982). However, the isometric ovarian growth in the Mediterranean sardine has been attributed to the lack of a size-dependent effects (Somarakis et al., 2004). These authors

further strengthen the appropriateness of the GSI index for the Mediterranean populations of ES, since they observed that fish length, geographical region, month of capture, and fat stage



had no effect on GSI, at least for females (Somarakis et al., 2004).

The evolution of monthly body condition index showed a complementary trend to GSI, indeed K_n displayed minima in January and December and maxima in July–August, when it is expected that the whole energy budget incoming from feeding would be devoted to somatic growth than gonadic (McBride et al., 2015). The males displayed lower body conditions than females at the spawning peak, supporting the main role of females that spend more energy than males in the gamete production along the season, and then a slower recovery of body condition (McBride et al., 2015).

The spawning period of European sardine displays variability in extension among different areas, although it is generally protracted from autumn to spring, both in the Atlantic and Mediterranean waters (Table 3). As in the study area, the spawning season lasting at least for 6 months with a peak in winter, except in the Adriatic Sea and Morocco waters (Table 3), where an inter-annual variability was recorded at least in monthly evolution of gonadic maturity stages (Amenzoui et al., 2006).

The present L_{50} results may appear divergent compared with previous studies on ES, especially from populations inhabiting in Atlantic areas; however, size at maturity estimates in the study area are in agreement with previous observations in the Mediterranean Sea (Table 3). Particularly, values recorded from the Aegean Sea are very similar (Tsikliras and Koutrakis, 2013); moreover, such similarity seems confirmed over time since results from the Strait of Sicily were also in agreement with Aegean Sea L_{50} in the 1990s as well as in western Mediterranean (Table 3). However, a huge discrepancy is notable with the Adriatic waters, where the L_{50} values, lower than all the other evaluations in both Atlantic and Mediterranean (Table 3), may be linked to the

oligotrophic condition occurring in this area (Zavatarelli et al., 1998), since the amount of available food influences the sexual maturation (McBride et al., 2015). In the Mediterranean basin (Sinovčić et al., 2008; Tsikliras and Koutrakis, 2013) as well as in the present research, the ES appeared to reach maturity at a lower size in male than in female (Table 3), as also observed in other small pelagic species (Pešić et al., 2013).

Along the study period, the inter-annual variability in L_{50} was observed to be resumed into two main levels, a higher and a lower level, at least for females (Figure 4). Within such estimates, the former group was more robust, as suggested by the higher $Pseudo-r^2$ as well as by the thinner confidence intervals. The plot of $Pseudo-r^2$ vs. the L_{50} estimates highlights more robust ogives at values of L_{50} around 125 mm (Figure 6, left panel). This plot also displayed a discrepancy between the time series 2009–2015 and the latter two years 2016 and 2017, which appear with lower $Pseudo-r^2$ values despite variability in L_{50} estimates. Indeed, in these two years, the samples were scarce compared with those of previous years, and such reduced sampling effort may affect bias associated to the L_{50} evaluations, as suggested by the plot of the L_{50} confidence intervals vs. the proportion of immature ES sampled per year (Figure 6, right panel). In particular, higher accuracy (low CI values) was observed when the proportion of immature individuals increased. However, the years 2016 and 2017 displayed lower accuracy, despite the higher proportion of immature specimens (Figure 6, right panel). Indeed, the observed variability in the monthly sampling per year as well as the number of fishes analyzed may appear as a potential source of bias in the L_{50} ogive fitting as observed in 2016 and 2017, when the total amount of individuals was considerably lower than in the previous years (Table 1).

TABLE 3 | Literature values of size at maturity of European sardine estimated in the Mediterranean Sea and Atlantic Ocean.

Area	Sampling period	Spawning season	$L_{50} F$	$L_{50} M$	References
Turkey (Aegean Sea)	1993–1996			121	(Tsikliras and Koutrakis, 2013) and references therein
Northern Aegean Sea	2000–2002	Oct–Apr	117	114	
Croatia (Adriatic Sea)	2002–2005	Nov–Feb		79	Sinovčić et al., 2008
Strait of Sicily (Central Med.)	2009–2014	Sep–Mar	123	118	Present study
Gulf of Lion (NW Med.)	2002–2008	Oct–Mar	121		Brosset et al., 2016
Gulf of Lion (NW Med.)	2009–2015		96		
Morocco (West Med.)	2019	Jan–Apr	133		Keznine et al., 2020
Alboran Sea (West Med.)	1983–1984		150	138	García and Perez de Rubin, 1998
	1989		138	136	(Silva et al., 2006) and references therein
	1991		125	128	
North France (Atlantic)	2000–2003			168	
South France (Atlantic)	1997–2001	Oct–Jun		140	Silva et al., 2006
Cantabrian Sea (Atlantic)	1986–1989			146	
	1990–2003			138	
Bay of Biscay (Atlantic)	2003–2018	Sept–Jun		143	Véron et al., 2020
North Galicia (Atlantic)	1986–1989			156	
	1990–2003			133	
South Galicia (Atlantic)	1986–1989			134	
	1990–2003			139	
North Portugal (Atlantic)	1984–1988	Oct–Jun		146	Silva et al., 2006
	1996–2003			143	
SW Portugal (Atlantic)	1984–1988			147	
	1996–2003			143	
West Portugal (Atlantic)	1947–2007			143	Silva et al., 2013
South Portugal (Atlantic)	1984–1988			139	
	1996–2003			124	
Gulf of Cadiz (Atlantic)	1996–2003			109	
Mauritania (Atlantic)	2003	Oct–Jun		162	Silva et al., 2006
Azores (Atlantic)	2000–2004			157	
Morocco (Atlantic)	1999–2001	Oct–Jun	158	158	Amenzoui et al., 2006
Morocco (Atlantic)	2014–2015	Winter	176	198	Abderrazik et al., 2016

Length at maturity was reported for female ($L_{50} F$) and male ($L_{50} M$) separately, when available for separated genders. Stock is identified by sampling area; sampling period is in years; spawning season is indicated, if known; size at maturity is indicated as total length (mm). Data are shown according an East–West gradient. About the estimates obtained in the present study, in the table the average values with higher accuracy and precision, obtained from years 2009, 2012–2014, and 2016 for females and 2012–2014 for males were included.

In the analyzed time series, monthly sampling gaps should be detected especially between December and January, mainly due to fishing seasonal closure; also, gaps in July–August were often recorded. Such type of sampling gaps has been already indicated in the literature as important source of bias affecting the stock assessment parameters estimation for ES. In the eastern Mediterranean Sea, sampling gaps were also linked to the fishing season closure in December–February and to the high proportion of juveniles sampled during this period, which may inflate the age 1 class (Tsikliras and Koutrakis, 2013). Certainly, since L_{50} is preferably estimated by spawning season samples, monthly gaps should be avoided in this period, as observed in 2016 (Table 1). Furthermore, most of the immature fish is rejected directly on board after catch because they are found to be under the legal size; therefore the presence on board of independent observers should allow to obtain samples of adequate proportion of smaller

individuals, which probably include the higher presence of immature fish.

Otherwise, the absence of trends in L_{50} as well as the observed variability among years in both genders would be linked to pelagic ecosystem flexibility. As in several pelagic fish species, maturity is linked to the environmental productivity (McBride et al., 2015), also in the case of sardine in both Atlantic and Mediterranean waters (Silva et al., 2006, 2013). Silva et al. (2013) postulated that an increase in temperature may induce in sardine a maturation at smaller length, and vice versa, and that higher temperatures improve body condition through increased feeding efficiency or a combination of both. Lower temperature associated with higher food availability within an upwelling system, which is common in the study area (Bonanno et al., 2014), was proved to enhance the condition, and consequently maturation of smaller individuals in different pelagic fish species

(Parrish and Mallicoate, 1995; Watanabe and Yatsu, 2006). A wide research carried out in several Mediterranean areas, including the study area, described a decreasing trend in body condition as well in maximum length in sardine during the last decades (Brosset et al., 2017). These decreases are in agreement with other observations, such as reduction in biomass and biological state within the basin (Vasilakopoulos et al., 2014; Tsikliras et al., 2015). In the same period, fluctuations of sea surface temperature and chlorophyll concentration were observed along the whole Mediterranean Sea (Brosset et al., 2017), including the study area particularly from 2009 onward (Basilone et al., 2020). Variability in chlorophyll concentration, temperature, and food retention have been recognized as driven for phenotypic flexibility phenomena, which may determine changing the size at maturity (Wertheimer et al., 2004). Reduction in size and age at maturity have been reported for a large number of commercial fish species (Jørgensen et al., 2007; Kuparinen and Merilä, 2007) due to environmental variation, fishing intensity or a combination of both (Marshall and McAdam, 2007). Moreover, variation in size at maturity with latitude is a common feature among Clupeiformes in European waters (Ganias, 2014), as observed both in sardine (Silva et al., 2006) and anchovy (Huret et al., 2019).

CONCLUSIONS

The analysis of such time series permitted not only to give more robustness to the L_{50} estimates, but also to highlight gaps in the sampling program, which in some year heavily biased the L_{50} calculations. The main concern from the present study suggests to reduce as much as possible the gaps in monthly distribution of samples from the commercial vessels and, possibly, to increase the sampling on board, in order to record also possible fishes under minimum legal size discarded at sea. Moreover, the proper integration of scientific survey data into commercial sampling data would provide a wider samples coverage, improving stock assessment evaluations as well as more precise control rules (e.g., minimum legal size). Fish species should be caught only within a specific window of their size, with a lower size limit excluding the immature individuals and an upper size limit excluding fishes with the greatest reproductive potential (Coleman et al., 2000), since bigger size spawner guarantee a better recruitment (Marshall and Frank, 1999). Thus, a reduction

in size at maturity would compromise reproductive potential as well as stock suitability levels. Therefore, new efforts would be devoted to better integrate the commercial and scientific surveys sampling programs, within the DCF. Recently, the European Court of Auditors pointed out how the European commission together with the Member States are responsible for the failure of the EU fishery policy in the Mediterranean Sea. In particular, they highlighted among others important factors that in the Mediterranean, where fisheries management is mostly linked to limits on fishing effort (and not catches), fishing rates were at twice sustainable levels, therefore encouraging Member States to increase the amount of funds related to conservation measures (European Court of Auditors Special Report, 2020).

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: Due to the data policy of the Research Project (Piano di lavoro Raccolta Dati Alieutici - REG. (UE) N. 508/2014 relativo al Fondo europeo per gli affari marittimi e la pesca (FEAMP) e REG. (EU) N. 2017/1004) the datasets analyzed in this article cannot be made publicly available. Requests to access these datasets should be directed to <https://dcf-italia.cnr.it/web/#/request-data>.

ETHICS STATEMENT

No use of live animals has been required for this study and no specific permissions were needed for the sampling activities in all of the investigated areas, because the target species is commercially harvested (neither endangered nor protected) and it was caught in areas where fishing is allowed.

AUTHOR CONTRIBUTIONS

GB, RF, MP, and AG: data curation. MB and GB: formal analysis and validation. AB: funding acquisition and project administration. RF and GB: investigation, methodology, and writing—original draft. SA, IF, and GG: software. GB: supervision. SM, MB, SA, AB, and SG: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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