Electronic tagging of Bluefin Tunas from the Maltese spawning ground suggests size-dependent migration dynamics

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Abstract The purse seine fishery in the Mediterranean represents about 60% of the international catch for Atlantic Bluefin Tuna (*Thunnus thynnus*). Yet, tagging operations from this segment of the fisheries remain rare and despite its potential importance for management, several aspects related to the migratory behavior of Atlantic Bluefin Tuna from these areas remain unaddressed. In the present manuscript, we report the results of two tagging operations carried out on a commercial purse seiner during two consecutive years in the spawning ground around the Maltese islands in the Central Mediterranean Sea. During these operations, eight individuals were tagged and the results showed that the larger fish (> 200 cm) undertook large-scale migrations outside the Mediterranean, whereas smaller individuals did not. This study suggests that size might affect the migratory behavior of Atlantic Bluefin Tuna, and underlines the potential of large-scale tagging operations from spawning grounds to address scientific questions having significant management implications.

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Background

Atlantic Bluefin Tuna (*Thunnus thynnus*, ABFT) is an economically important and emblematic species known for its large-scale migratory behavior (Mather et al., 1995; Rooker et al., 2007). The species is managed as two stocks by the International Commission for the Conservation of Atlantic Tunas (ICCAT), but mixing between the western and the eastern units is well documented and future approaches developed for the management of this species integrate this aspect (Puncher et al. 2018; Rodríguez-Ezpeleta et al. 2019).

Electronic tagging is an important tool to study the spatial ecology of ABFT and derive the probability of the fish being in a given area (Block et al. 2005). ABFT generally displays fidelity to the spawning site and fish entering the Mediterranean Sea are assumed to belong to the Eastern stock (EABFT), whereas fish entering the Gulf of Mexico are assumed to belong to the Western stock (Fromentin and Powers 2005).

Even though the spawning migration sustains the purse seine (PS) and trap (TP) fisheries whose catch add up to about 75% of the total allowable catch of the Eastern stock, many aspects of these migrations remain to be uncovered (ICCAT 2017). For instance, the number of fish migrating in and out of the Mediterranean and the effect of fish size as well as the effect of environmental conditions on these migrations have not yet been fully described despite their importance for the exploitation and conservation of EABFT.

Tagging EABFT from recurrent spawning grounds has several advantages to answer these questions. Spawning grounds concentrate a very large number of individuals of diverse size, over a reduced space, in known areas and over a well-defined and known time-period. During the peak spawning season in June, the very intense PS fishing activity provides a good opportunity to catch EABFT. Major known recurrent spawning grounds for EABFT are the southern Balearic Islands, the south Thyrrenian sea, the central Mediterranean and around Cyprus in the eastern Mediterranean (Fromentin and Powers 2005). Despite these advantages, tagging EABFT from these areas during the spawning season has seldom been explored as it remains a challenge. Instead, in the Mediterranean, electronic tags are often deployed from recreational fishing boats allowing fish to be caught by rod and reel and to deck the fish in good condition (Fromentin and Lopuszanski 2014; Cermeño et al. 2015). However, in spawning grounds such a technique may not be efficient because the spawning grounds are not easily accessible from the shore, because the long fighting time needed to draw in large individuals might not allow many individuals to be tagged in good condition and also because during spawning season foraging is not the main activity of ABFT. Tagging large Bluefin Tuna with this technique often requires a lot of time spent at sea and demands a lot of human resources.

The French PS fishery has been specializing since the mid-1990s in operating in the spawning grounds. Their current technique enables the capture of more than a hundred tons of mature fish in one set, several thousand individuals, which are kept alive to be transferred into a farm cage on the fishing grounds. These vessels employ specific practices that allow them to scout large areas, which is enhanced by a platform high above the sea level allowing for a good visual inspection of the sea and state of the art echosounders for surveying the water column. Furthermore they have large decks, cranes and a skilled crew with divers that allow for a secure handling of the fish. Such a logistical set-up is ideal for tagging, but still requires the employment of the specific techniques that have been reported in recent work (Rouyer et al. 2019, 2020).

The present manuscript reports on the results obtained from 2 years of tagging from PS in the central Mediterranean (south of Malta) spawning ground in 2018 and 2019. Results obtained from the 2019 operation are merged with those from the first operation (Rouyer et al. 2020) to provide preliminary results on the migratory dynamics from this spawning ground. The manuscript presents the routes taken by fish of different sizes. The tracks and performance of the operations are discussed in the light of the current knowledge on EABFT migratory dynamics studied through electronic tagging.

Materials and methods

Tag deployment

The deployment of tags from a PS in the Mediterranean requires a specific set-up as it involves complex logistics, interactions with the fishing activity, and deals with large fish contained in a reduced space, as has been detailed in previous work (Rouyer et al. 2020). A total of 8 PSAT tags were deployed during two operations in 2018 (3 tags) and 2019 (5 tags). Since the methodology employed in 2019 is similar to the 2018 operation and detailed elsewhere (Rouyer et al. 2020), only the specifics of the 2019 deployments are detailed below.

In 2018, the three tunas were tagged onboard the purse seine vessel Saint Sophie François III (SSFIII, ICCAT serial number ATEUFRA00065), which operates with its sister ship Saint Sophie François II (SSFII, ICCAT serial number ATEU-FRA00064). The three fish were tagged on June 20th, 2018. In 2019 the deployments took place onboard the same vessels. A school of ABFT was captured in the early morning of June 7th, and since the cage transfer was programmed to occur the following day, there was enough time for tagging. The tagging operation took place following the exact same protocol applied during the 2018 session, with only one minor improvement: the tagged fish were not released outside of the PS net, but inside, in a location where the net was subsequently opened to let the tunas escape. This reduced the transfer time of tagged ABFT from the deck to the water by about 30 s by simplifying the maneuvering of the crane over the purse seine.

A total of 8 tunas were tagged over both operations. Building on the experiences of 2018, the 2019 operation went more smoothly and five tunas were tagged during one purse seine set, compared to three in 2018. Three tunas were tagged at midday the first day (07/06/2019) and two in the early morning the next day (Table 1). The tagging session had to be interrupted by the arrival of the transfer cage in the morning, but given that two fish were tagged in less than 20 min, more tags could probably have been deployed. Although the fish from the 2019 PS set showed a lower feeding activity when exposed to bait compared to 2018, when a tuna was hooked, our technique allowed the tagging team to catch, deck, tag, and release the individuals in a very short amount of time (less than 10 min). All five fish spent less than 2 min on the deck and were released in good condition as they were able to let themselves out of the stretcher without any outside help.

Wildlife Computers' MiniPATs were used for the deployments and were programmed to release after 360 days in order to capture a yearly cycle of migration. The total amount of data messages to be transmitted cannot be too large and in the case of long deployments it is often necessary to prioritize some data over others. It was chosen to not generate temperature time series messages and to generate depth time series every 4 days based on a 10 min sampling. Daily summary messages on Temperature and Depth were also produced.

Track analysis

The GPE3 state-space algorithm from Wildlife Computer was used to estimate the tracks from the data recorded by the tags. Animal speed is the main prior for the algorithm and the values 3, 5, 7, 10, 15, and 20 km h^{-1} were tested in order to identify the most likely trajectory through the goodness-of-fit score provided. This range was set arbitrarily to reflect a progression between low and large speeds that could be reached during different periods of the life-cycle (e.g., foraging and migrating). For the purpose of this study, the outputs of the GPE3 algorithm were averaged by day.

Table 1 Summary information for the tags deployed during the 2018 and 2019 tagging operations off Malta. The number of messages is a proxy for the amount of data transferred by each tag

Tag	Size SFL (cm)	Deployment date and time (local)	Retention (days)	Pop reason	Messages
BFT1	226	20/06/2018 11:30	72	Broken pin	3996
BFT2	189	20/06/2018 14:30	62	Broken pin	2488
BFT3	206	20/06/2018 15:30	32	Broken pin	797
BFT4	165	07/06/2019 12:05	71	Broken pin	1290
BFT5	163	07/06/2019 12:26	288	Unclear	30
BFT6	220	07/06/2019 13:05	360	Full term	1370
BFT7	200	08/06/2019 5:56	360	Full term	716
BFT8	176	08/06/2019 6:08	95	Unclear	672
Summary (mean ± SD)	193 ± 24	-	168 ± 142	-	1420 ± 1263

Results

Retention of tags

The retention time of the tags deployed during the 2019 operation was 235 (±142) days on average, a strong improvement compared to the 55 (±21) days average obtained from the 2018 operation (Table 1). For the two fish BFT6 and BFT7, the tag remained attached the full 360 days as planned and tag BFT7 was physically retrieved in 2021. The tag deployed on BFT5 popped off after 288 days in the Adriatic Sea near Ravenna. Tag BFT8 popped-off after only 95 days in the Myrtoan Sea in Greek waters in a harbor next to Athens. The retention time for the tag deployed on BFT4 was shorter, as the tag popped-off after 71 days not far from the deployment area.

Tracks

The number of messages transferred was noticeably lower in 2019 compared to 2018, ranging from 30 to 1370 messages, whereas in 2018 it ranged from 716 to 3996 messages (Table 1). This affected the quantity of data retrieved from the tags and the track reconstruction. For instance, even though the tag deployed on BFT5 remained attached for 288 days, the amount of data transferred (i.e., number of messages) was low, which made the geolocation impossible (Table 1). In the same vein but not as drastically low, the tag deployed on BFT7 only transmitted 716 messages; fortunately its physical retrieval allowed access to the full extent of the data collected. This left 7 exploitable tracks from the 8 tags deployed, although some had large light data gaps that needed to be handled.

BFT1, a 226 cm fish, displayed a migration outside of the Mediterranean in mid-July (Fig. 1). The tag remained attached 72 days (Table 1). After reaching the Atlantic, the fish headed north and spent some time in August in the southern Bay of Biscay, before the fish went to northwest Ireland where the tag popped-off. The best goodness-of-fit score was achieved by a 20 km h^{-1} prior (Table 2). BFT2, a 189 cm fish, did not seem to have moved very much from the area of deployment over the two months that the tag remained attached. The best goodness-of-fit score was achieved by a 5 km h^{-1} prior. The tag on BFT3, a 206 cm fish, only remained attached about a month, but its route was comparable to the route of BFT1 in terms of timing and location, which suggested that the fish was aiming to exit the Mediterranean in mid-July, before the tag popped-off. The best goodness-of-fit score was achieved by a 20 km h^{-1} prior.

For BFT4, a 165 cm fish, the prior providing the highest score through the GPE3 algorithm was 10 km h^{-1} (Table 2). The tag remained attached 71 days, as long as for BFT1, yet the track was very different (Table 1). The track showed that the fish did not leave the vicinity of Malta. The tag deployed on BFT5, a 165 cm fish, only transmitted 30 messages, which did not allow for reconstructing the track. The tag popped-off in the Adriatic Sea, near Ravenna. For BFT6, a large 220 cm fish, the prior providing the highest score through the GPE3 algorithm was 20 km h^{-1} (Table 2). The track obtained showed a complete migration loop over a year from the Mediterranean, out into the Atlantic and back into the Mediterranean (Fig. 1). The fish left the Mediterranean in Mid-July, headed north to a large area of the northeast Atlantic southeast of Iceland, where it stayed between August and November. It then headed southwest to about −40°W/50°N during November through to January, before going back east. In February, the fish headed north to the area visited in the fall, before coming back in June into the Mediterranean. The tag popped-off near Gibraltar following the programmed duration specification. For BFT7, also a large 200 cm fish, the highest scores achieved through GPE3 was with the 15 km h^{-1} prior (Table 2). As for BFT6, the track displayed a complete migration loop over a year from the Mediterranean, out into the Atlantic and back into the Mediterranean. The fish migrated outside of the Mediterranean in July and headed towards the Bay of Biscay. In August and September, it went further north to the Irish Sea and the western English channel before going back to the Bay of Biscay and heading west between October and December. Between January and February BFT7 seemed to forage in the area between −40°W/40°N and −25°W/40°N while it started to slowly head back towards the east. In March and April, BFT7 went back in front of the Bay of Biscay, before heading towards the Mediterranean where it entered in May. The tag popped-off in June, as planned. The tracks of BFT6 and BFT7 suggested a long-term synchrony as their latitude and longitude displayed similar general

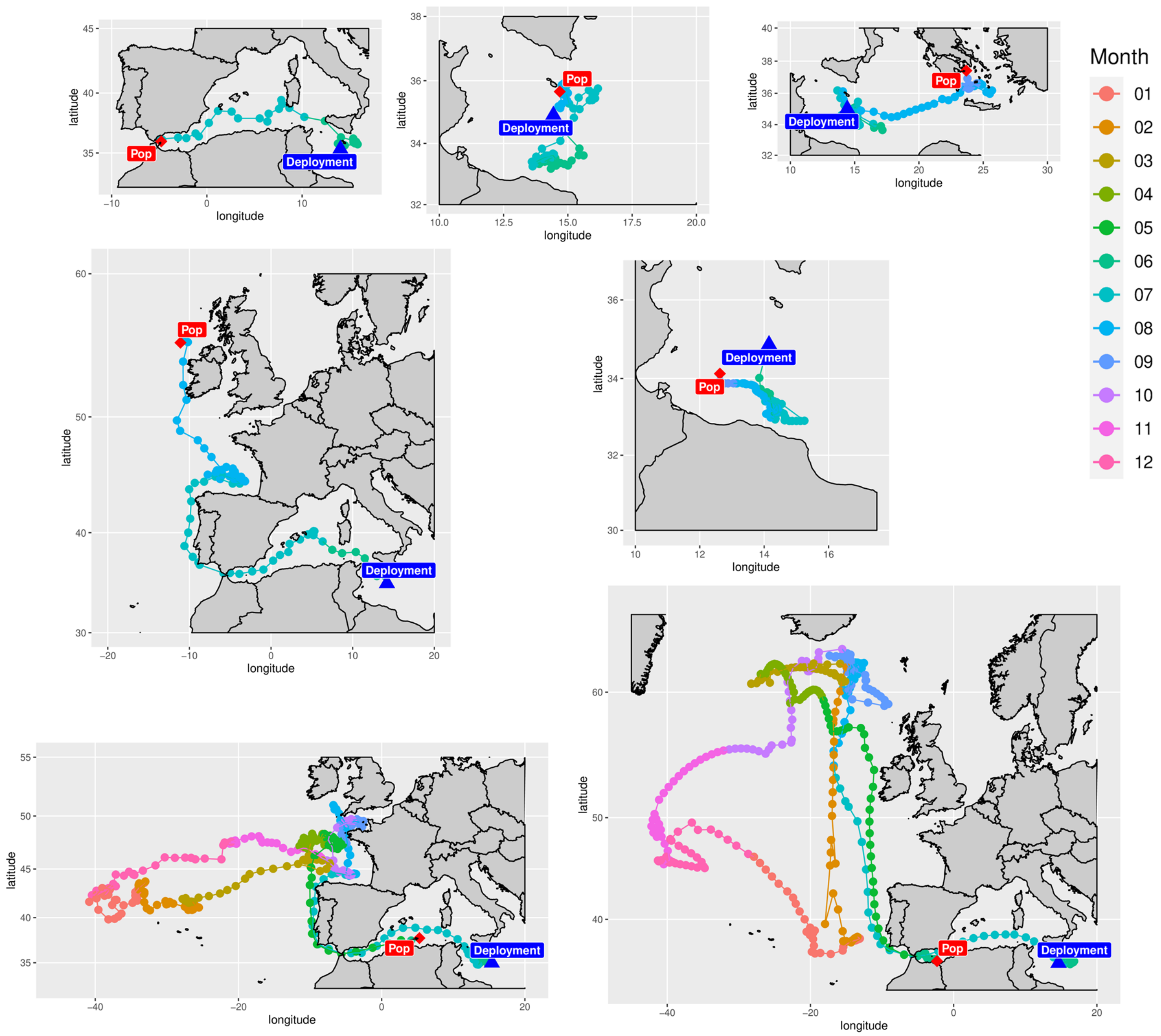
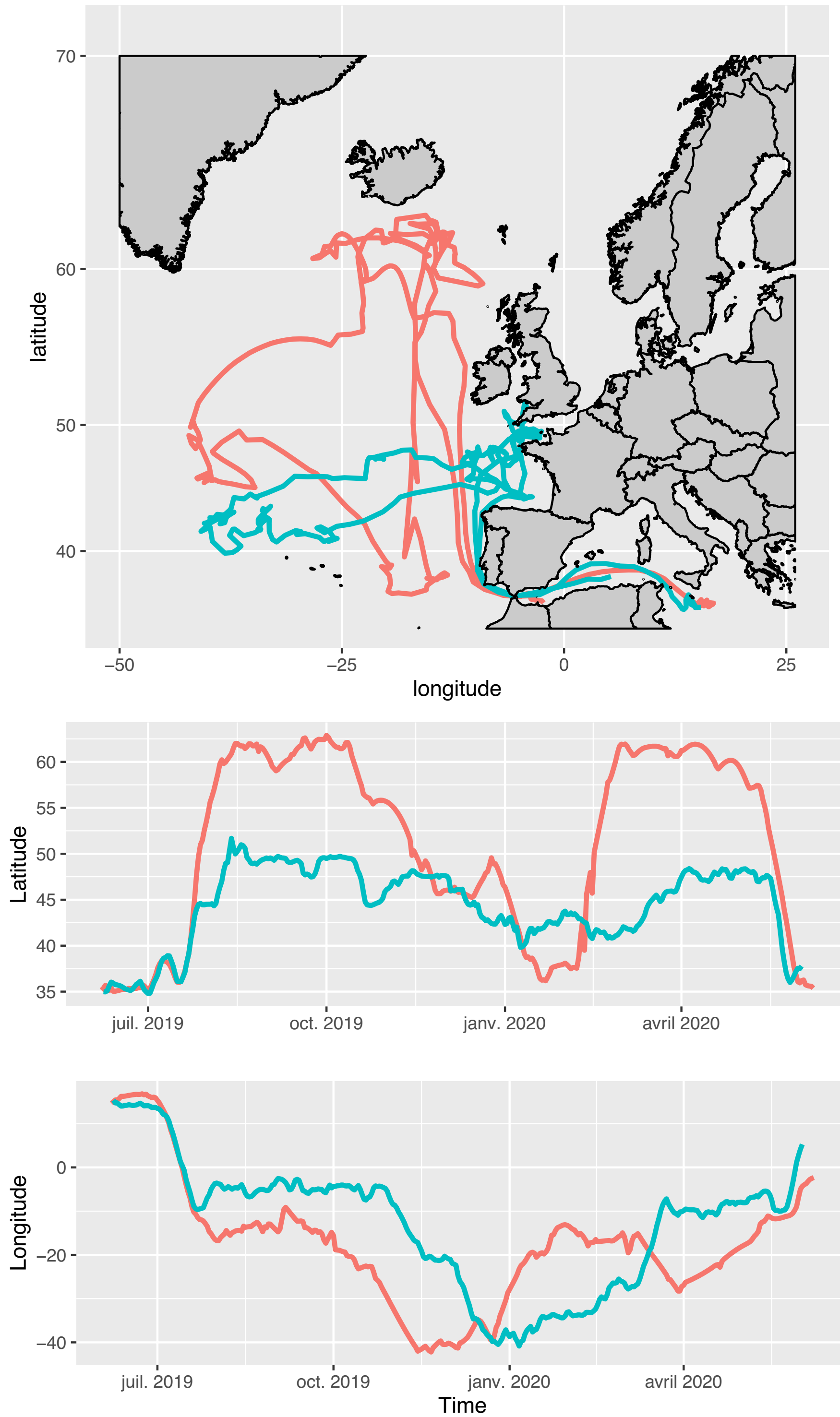


Fig. 1 Tracks obtained through the GPE3 algorithm using the speed priors providing the best goodness-of-fit scores. The different colors along the tracks indicate the different months. For BFT7, a few and very coastal data points were excluded to improve clarity

Table 2 Scores obtained through the GPE3 algorithm for different speed priors (km h^{-1})

Tag	3	5	7	10	15	20
BFT1	NaN	NaN	48.45	50.01	50.83	51.11
BFT2	58.79	60.03	60.02	58.9	59.01	57.01
BFT3	NaN	51.91	59.71	63.57	65.98	66.33
BFT4	65.24	68.78	69.8	70.13	69.89	69.44
BFT6	22.6	37.47	46.32	48.13	48.4	48.55
BFT7	NA	55.60	56.77	57.92	58.01	57.95
BFT8	53.27	58.36	60.18	61.18	62.44	62.93

Fig. 2 Migrations of BFT6 (red) and BFT7 (blue) that displayed a loop from the Mediterranean to the Atlantic and back again into the Mediterranean. The top panel shows the two tracks, the middle one displays the evolution of latitude over time, and the bottom one the evolution of longitude over time



patterns (Fig. 2). In particular, January marked a change for both fish as they initiated their way back to the Mediterranean via the Bay of Biscay. In the case of BFT8, a 176 cm fish, the prior providing the highest score through the GPE3 algorithm was 20 km h^{-1} (Table 2). It displayed an eastward movement from the tagging location to the Greek waters. The track showed that the fish stayed south of Malta during June and July, before moving to Greek waters in August, where it stayed until the tagged popped off in September (Fig. 1).

Discussion

Tag retention and reporting are key issues for the tagging of large pelagics, and which have a large impact for ecological studies (Musyl et al. 2011; Stokesbury et al. 2011; Lutcavage et al. 2015; Jepsen et al. 2015). For large migratory species such as ABFT, this could lead to an incomplete view of the habitat visited and reduce the possibility to infer information about ABFT migratory dynamics (Arregui et al. 2018).

In the present case, tag retention is a particularly critical aspect due to the complex nature of the access on the site of operations and the interaction with the timing of fishing operations. The particularity of the tagging operation described here, with the special logistics at sea on commercial purse seiners during the spawning season and on spawning grounds, makes it impossible to "try again later" and tags that failed directly impacted the results of the operation. The comparison between the 2018 and 2019 retention times showed a very clear improvement, which appeared to be mainly driven by the reduction in the number of "broken pin" events during the 2019 operation (Table 1). In the 2019 operation, two out of the five tags deployed remained attached over the whole planned duration (360 days) and another one remained attached 288 days. The reduced retention times obtained from the two other tags came from a "broken pin" event (BFT4) and a potential recapture event (BFT8), which may have prematurely ended the deployment. Compared to other studies on a comparable pool of individuals, the overall retention time was found to be good and suggests that the deployment protocol was appropriate and kept stress at a low level (Aranda et al. 2013; Abascal et al. 2016; Tensek et al. 2017). The improved retention time in 2019 was unfortunately impaired by a poor amount of messages transferred for which no clear explanation was obtained and this reduced the information extracted from these successful deployments (Table 1). This was particularly problematic for the tag deployed on BFT5 that remained attached 288 days but only transmitted 30 messages and could not be used to provide any usable track. For this particular case a battery failure was identified by the manufacturer.

Tracks for BFT1, BFT6, and BFT7, all of which exited the Mediterranean, showed that the fish turned north after their exit consistent with routes documented in other studies albeit from a different spawning ground (Aranda et al. 2013; Abascal et al. 2016; Tensek et al. 2017). The tracks for tags deployed on BFT6 and BFT7 showed a complete loop from the deployment location in the Mediterranean off Malta, involving exiting the Mediterranean in mid-July and coming back in the Mediterranean in June of the following year. BFT6 visited the area south of Iceland in September–October, known as a fishing ground for Japanese longliners, whereas BFT7 spent more time foraging in the Bay of Biscay and also visited Brittany, the Irish Sea and the western part of the English Channel. This migration pattern shows that fish spawning in the Mediterranean are connected to these locations where EABFT has been increasingly spotted during the past decade (Kimoto and Itoh 2017; Horton et al. 2020; Nøttestad et al. 2020; Jansen et al. 2021). It also shows that these fish tended to come back to the Mediterranean the spring of the following year, a behavior likely to be linked to a potential breeding event. These two fish, tagged one day apart, forming part of the same school and of comparable size, showed very different migration patterns but also some extent of long-term synchrony regarding the beginning of the "return" period to the Mediterranean; the results of these two tags underlines the benefit of tagging several fish from the same school to understand migration patterns (Fig. 2).

After 2 years of tagging in the central Mediterranean, one salient aspect is that the tracks showed that all of the 4 fish whose size was above 200 cm migrated outside of the Mediterranean during the month of July or attempted to do so (BFT3), whereas fish whose size was below 200 cm did not (Fig. 3). The tracks obtained from the tags deployed on the smaller fish did not display any movement that could suggest that they attempted to migrate outside of the Mediterranean. BFT2 and BFT4 displayed tracks that did not cover any distance in any preferential direction, as the fish tagged remained in the vicinity of their deployment area, south of Malta. The tag deployed on BFT8 displayed a movement towards Eastern Greece and popped-off not far off Athens.

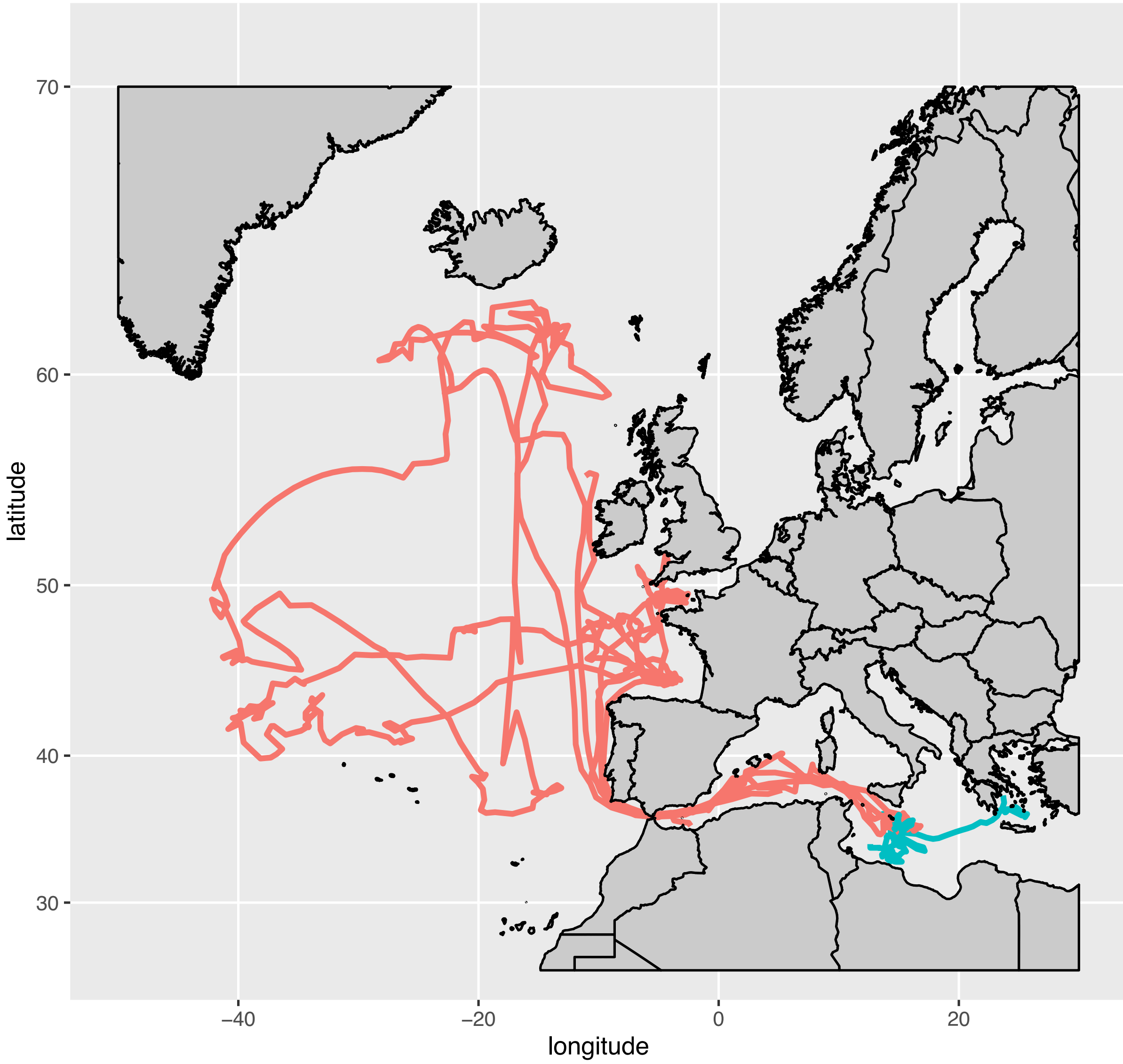


Fig. 3 Tracks obtained from the deployments in the Maltese spawning ground. The tracks for the fish with a size above 200 cm are in red and the tracks for smaller fish are in blue

EABFT post-spawning migrations outside the Mediterranean take place during the month of July and can happen until late August (Cermeño et al. 2015; Mather et al. 1995). In agreement, our results documented outward post-spawning migrations that occurred in mid-July. This showed that even if the retention times for the tags deployed on fish whose size was below 200 cm were not as long as desired, by the end of August the migration out of the Mediterranean should have already taken place and should have therefore been captured or hinted at by the tracks. This was not found to be the case. Results obtained by other tagging studies in the Mediterranean documented numerous deployments for several size classes but did not allow to compare the dynamics of fish below and above 200 cm because the retention times obtained for the few fish above 200 cm were too short to cover the post-spawning migration period (Cermeño et al. 2015; Fromentin and Lopuszanski 2014). For those studies, no fish was found to leave the Mediterranean with one exception, a 185 cm fish that came out of Gibraltar for a few days and came back in afterwards. When in other studies tracks covered the post-spawning migration period, the fish that were found to migrate outside of the Mediterranean were larger than 200 cm (Aranda et al. 2013; Abascal et al. 2016; De Metrio et al. 2005). An exhaustive analysis of the results obtained from tagging activities carried out through ICCAT or by other teams deploying tags in the Northeast Atlantic might help to deeper investigate this hypothesis, even though fish tagged in the Northeast Atlantic are more rarely smaller than 200 cm excepted in the Bay of Biscay (Horton et al., 2020; Tensek et al., 2017). The size for which the change in migratory dynamics is suggested by our results (i.e., 200 cm) cannot be easily explained as juvenile fish tagged in the Bay of Biscay have been found to make transatlantic migrations, proving that they are physiologically capable to achieve movements over large spatial scales (Arregui et al. 2018). If further work confirms this pattern, understanding why these changes in behavior occur around that size and whether inward migrations are also subjected to a size effect would be key questions to be answered. In that respect, the Bay of Biscay is a very interesting area where the juvenile fish that is found in large quantity is assumed to originate from the Mediterranean, whereas tagging results displayed early transatlantic movements and no evidence of entering the Mediterranean during the early years (Arregui et al. 2018).

Compared to the Balearic islands, only a few tags have been deployed in the Central Mediterranean. However, this is one of the main areas for the purse seine exploitation of EABFT and if our results are shedding some light on the migratory dynamics in this part of the Mediterranean, an increased tagging activity would be welcome to help bridging this gap. Our results show that large-scale tagging from spawning grounds has a strong potential to address important questions on EABFT ecology that are relevant to its management, particularly because it is related to a fisheries segment that represents about 60% of the total allowable catch. Similar operations planned in 2020 and 2021 had to be canceled because of the international sanitary situation, but the deployments planned in the coming years should significantly increase the number of electronic tags deployed; this will greatly increase the information required to better address the questions identified in the present manuscript.

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Author contribution All authors contributed to the study conception. The first draft of the manuscript was written by Tristan Rouyer and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The entire dataset generated during and/or analyzed during the current study are not publicly available yet but are available from the corresponding author on reasonable request.

Declarations

Ethics approval All applicable international, national, and/or institutional guidelines for sampling, care, and experimental use of organisms for the study have been followed (APAFIS #9005–2017022212232853 v6) and all necessary approvals have been obtained (tagging authorizations 2019/859076/FishNchip/000001 and 2019/859076/FishNchip/000002 from the French Ministry Department of Marine Fisheries and Aquaculture).

Competing interests The authors declare no competing interests.

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