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The comeback of Atlantic bluefin tuna (*Thunnus thynnus*) to Norwegian waters

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ABSTRACT

We document that Atlantic bluefin tuna (BFT) began making a comeback from 2012 onwards into Norwegian waters, after several decades of absence, in parallel with an overall increased abundance recorded for eastern BFT. This study explores the distribution, biology and ecology of BFT reestablishing in Norwegian waters. We analyzed commercial catch and bycatch data including biological data on weight, length and age of BFT from 2016–2018. Predominantly larger (overall range in catches: 120 – 465 kg in weight and 184 – 297 cm in straight fork length (SFL)) adult individuals between 6 and 14 years old have recently started to revisit Norwegian waters. Numerous recently documented BFT observations were reported in this study, and a significant increase was detected from 2012 ($n = 1$) to 2018 ($n = 105$) ($p < 0.01$). Schools of BFT were observed predominantly from June to December, including the northernmost registered observation in history recorded at 76.2 °N in September 2018. Atlantic bluefin tuna has now reestablished and has shown a positive comeback to its historical migration patterns in Norwegian waters, where it has expanded its feeding areas towards the north.

1. Introduction

Atlantic bluefin tuna (BFT) (*Thunnus thynnus*) is the largest of all tuna species and is highly migratory (Fromentin and Powers, 2005). It may reach 3.2 m in length, weigh more than 700 kg (Cort et al., 2013) and reach a life span of nearly 50 years (ICCAT, 2019). The total BFT stock in the Atlantic Ocean comprises two subcomponents: the eastern Atlantic stock (EBFT), which mainly spawns in the Mediterranean Sea, and the western Atlantic stock (WBFT), which mainly spawns in the Gulf of Mexico (Fromentin and Powers, 2005).

The EBFT stock is significantly larger than the WBFT stock and has shown a consistent growth in terms of abundance for more than a decade (ICCAT, 2018, 2019). Eastern Atlantic BFT is at present healthy and sustainably managed, after being nearly at the brink of a collapse only around 15 years ago (ICCAT, 2019).

Bluefin tuna has probably been feeding along the Norwegian coastline and in offshore waters for thousands of years (Tangen, 1999; Eidshaug and Sauvage, 2016; Nøttestad et al., 2017), due to the high abundance of nutrient-rich schooling prey species such as mackerel (*Scomber scombrus*), herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), and lesser sandeel *(Ammodytes marinus)* found there (Tangen, 1999; Nøttestad et al., 2017; ICES, 2019). Historically, BFT visited Norwegian waters from early July until late October to feed (Hamre and Thiews, 1964; Nøttestad and Graham, 2004; Cort and Nøttestad, 2007). During the feeding season, the majority of individuals visiting the Norwegian coast were adults weighing between 50 and 520 kg (Hamre, 1962; Aloncle et al., 1972; Nøttestad and Graham, 2004; Nøttestad et al., 2017; ICCAT, 2019). The migration pattern of BFT differed according to size and age composition of individuals belonging to different schools (Hamre and Tiews., 1964). Usually the first BFTs to reach Stad (62 °N) at the start of the season were the oldest (12–15 years) and largest individuals (> 150 kg) (Nøttestad and Graham, 2004). These individuals migrated further north along the Norwegian coastline, and some were observed as far north as Laksefjord in Finnmark county (> 70 °N) (Hamre, 1962; Hamre and Tiews, 1964; Tangen, 1999).

Norway had one of the largest fishing fleets targeting BFT in the Northeast Atlantic from 1950 to 1964 (Nøttestad and Graham, 2004). Nearly 470 purse seine-vessels participated in the fishery along the Norwegian coastline, covering fishing grounds from the Oslo fjord in the south up to Troms county in the north (Tangen, 1999). Up to 15,000 metric tons of BFT were caught within a single fishing season (Hamre and Tiews., 1964; Nøttestad and Graham, 2004, 2005; ICCAT, 2016).

There was a drastic reduction in the distribution and extent of BFT migration patterns in Norwegian waters from ca. 1965 onwards, that led to the gradual decline of the Norwegian BFT fishery (Nøttestad and

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Graham, 2004). The reasons for this are uncertain (MacKenzie and Myers, 2007; Cort and Nøttestad, 2007), but major international overfishing of both juvenile and adult fish, probably occurring for decades, is regarded as a potential major reason for the historical decline of BFT in Norwegian waters (ICCAT, 2018). Studies indicate that recruitment overfishing as well as growth overfishing of juvenile BFT around spawning areas in the Mediterranean Sea during the 1950s and 1960s, and in the Bay of Biscay and off the coast of western Africa during the 1960s and onwards, were the main contributors to the decline of the East Atlantic stock (Cort and Nøttestad, 2007; Cort and Abaunza, 2015, 2016; Cort, 2017; Nøttestad et al., 2017; ICCAT, 2018). Altogether, it is likely that BFT migration patterns have been affected by interactions between environmental, trophic and fishing processes (Fromentin, 2009).

The objective of this study was to obtain new insights into the abundance, biology, distribution and ecology of BFT in Norwegian waters after the comeback. We determined basic biological parameters for BFTs caught in Norwegian waters from 2016–2018 and we drew a comparison between present size ranges and historically known size ranges in Norway. We retrieved and mapped observational data from Norwegian waters in space and time after the comeback. Finally, we tested the probability of encountering small and large school sizes of BFT at specific times of the year.

2. Materials and methods

2.1. Capture data from the fishery

The data used for analyses in this study were collected from commercial catch statistics at the Norwegian Directorate of Fisheries and at the International Commission for the Conservation of Atlantic Tunas (ICCAT), as well as from structured data on BFT observations available from the Institute of Marine Research (IMR).

Straight fork length (SFL), curved fork length (CFL) and round weight (RWT) were measured as defined in Lombardo et al. (2016). The two different length measures (SFL and CFL) were taken indistinctively with no reference to overall fish size. All measurements were standardized to centimeters (cm) for length, and kilograms (kg) for weight.

The numbers of BFTs sampled from directed fishery catches and from bycatches with the corresponding conversion factors for RWT used each year from 2016–2018, are displayed in Table 1. The age distribution for 2018 was estimated using an age-length key derived from age-determined BFT individuals sampled in 2016 and 2017 (Table 2).

2.1.1. Length/weight relationship and condition

The length/weight relationship for BFTs caught between 2016 and 2018 is expressed by the following equation,

$$W = \alpha L^{\beta} \tag{1}$$

where W is body weight, α is a coefficient related to the body form of the fish, L is length (cm) and β is the growth constant (Edwards, 1984; Beverton and Holt, 1957; Draper and Smith, 2014). The condition of each BFT caught between 2016 and 2018 was estimated using Fulton's Condition Factor (K) (Ricker, 1975).

Table 1
Number of Atlantic bluefin tunas (BFTs) sampled from target catches and bycatches with the corresponding conversion factors for RWT used each year from 2016 to 2018.

	2016	2017	2018
Samples from targeted catch	191	234	56
Samples from bycatch	10	14	5
Conversion factor	1.16	1.28	–

Table 2
Age-length key made from age-determined Atlantic bluefin tuna (BFT) individuals from 2016 and 2017. Straight fork length (SFL) is divided into 5 cm categories with numbers of BFT counts per age corresponding to each length category.

Length categories	Age 6	7	8	9	10	11	12	13	14	Total
185 – 189	1	1		1						3
200 – 204			8	4	1					13
205 – 209		3	8	10	4		1			26
210 – 214		2	12	29	8	3	1			55
215 – 219			10	27	32	11	2	1		83
220 – 224			8	25	29	12	3	1		78
225 – 229			1	7	26	17		1		52
230 – 234				6	15	17	4	1		43
235 – 239				4	10	7	10	2		34
240 – 244				1	5	5	3	3	1	18
245 – 249					1	1	3	1		6
250 – 254					2	1	1			4
> 255							2			2
Total numbers	1	6	47	114	133	74	30	10	1	416

2.2. Age determination

The ages of 82 % of the BFTs (n = 416) caught in the directed fishery or as bycatch inside the Norwegian EEZ between 2016 and 2017 were determined based on the analysis of the first dorsal fin spines in each individual, as described in Arrizabalaga et al. (2019). Each year, from 2016–2018, samples were sent to AZTI Technalia in Spain for age determination. Fin spine sampling and sectioning procedures, examination, and interpretation were performed as described by Rodríguez-Marín et al. (2012) and Luque et al. (2014). There were no age-determined individuals available from 2018 for this study. Therefore, the age was estimated for all fish caught in the directed commercial fishery (n = 56) and from bycatches (n = 3) and that had been length-measured during 2018. Age estimations were conducted using the FSA R-package (Ver. 0.8.22.9000) (Ogle et al., 2018) in R-statistical software (R Development Core Team, 2013), and were based on the age-length key retrieved from age-determined individuals from 2016 and 2017 (Table 2).

2.3. Observational data

Observations of BFT made in recent years were collected through several platforms of communication, such as social media, various news magazines, the commercial fishing fleet and the Norwegian reference fleet. To facilitate this process and to conveniently organize incoming data, an online observational questionnaire was also distributed via these communication platforms in August 2018. Here, observers registered their observations and the data were sent to us. Documentation of BFT observations from footages, such as photographs or videos (surface and underwater), were particularly important, as these would allow the validation of reported observations, even though there were no strict requirements imposed for an observation to be validated.

Observations were also obtained from commercial catches reported by the target fishery from 2016–2018. Each attempt to catch BFT using purse seines and each actual catch was registered as an observation. If no information was given about the number of BFTs observed during catch attempts, 1–5 individuals per attempt or the exact number of BFTs caught in each catch were registered as numbers of BFT observed. The category 1–5 corresponds to the modal school size of the observations.

2.4. Data presentation and statistical analysis

Maps of the Norwegian coast with bubble plots of BFT observations made inside the Norwegian EEZ for 2016, 2017 and 2018, were generated using the ggmap-package (Kahle and Wickham, 2013) in R-statistical program. All statistical analyses were conducted in R-statistical software, where $p < 0.05$ was chosen as the level of significance, with a 95 % confidence interval for all tests. We analyzed the overall change in BFT distribution and migration pattern within Norwegian waters in space and time.

A one-way ANOVA was performed for individual BFT weight, SFL and condition per year. If the one-way ANOVA produced a significant p-value ($p < 0.05$) between years, a post hoc Tukey HSD-test was performed to determine which years differed significantly from each other. A Chi-square goodness of fit test was performed to test for differences between the quantities of observations that were made each year from 2012 to 2018 and the expected probability, assuming an even distribution of observations over the years. A binomial logistic regression analysis was performed for the years 2016–2018 on observed school sizes, (categorized as “small” and “large”) versus Julian day, and it included “days” as a continuous predictor variable. “Small” was defined as a school size of 1–10 individuals while any group above ten was considered as “large”. The time span measured in days started in July and ended in December.

3. Results

Based on annual documentation of observations from 2012 and catch and by-catch data from 2015 onwards (Table 1), it appears that BFT has started to reestablish in Norwegian waters. The tuna caught in Norwegian waters between 2016 and 2018, ranged from 120 to 465 kg in weight, 184–297 cm in SFL and 6–14 years in age (Table 2). Most of the 11 BFT by-catches reported were collected by different types of trawl vessels or by commercial fishing vessels targeting mackerel, Atlantic horse mackerel (*Trachurus trachurus*), herring, blue whiting and shrimp (*Pandalus borealis*). Predominantly larger (overall range in catches: 120 − 465 kg in weight and 184 − 297 cm in straight fork length (SFL)) adult individuals between 6 and 14 years old have recently started to revisit Norwegian waters (Table 3).

No significant differences in individual BFT weights were found between years ($p > 0.05$) while SFL was significantly higher in 2017 than in 2016 ($p < 0.01$) and 2018 ($p < 0.01$) (Fig. 1). Condition (K) was significantly higher in 2016 than in 2017 ($p < 0.01$) and 2018 ($p < 0.05$). The age-distributions of BFT from 2016–2018 are shown in Fig. 2.

A total of 213 observations of BFT in Norwegian waters were obtained between 2012 and 2018 (Fig. 3) and a significant increase in observations was detected during this time (Chi-square value = 288.6, df = 6, $p < 0.01$). BFT was observed predominantly from July to October, but observations of BFT were also made in Norwegian waters during winter (Table 4).

Visual observations of BFT jumping and/or hunting at the surface, represented the majority of registered observations from 2016–2018. A total of six cases of BFTs trapped inside fish farm pens were reported between 2016 and 2018. These individuals managed to become trapped inside the pens by penetrating through the walls and the steel wires surrounding the fish pens. Altogether three individuals were observed as being stranded. Types of observations collected in this study are summarized in Fig. 4.

Table 3
Minimum, mean and maximum weights, straight fork lengths (SFL) and ages of Atlantic bluefin tunas (BFTs) caught in Norwegian waters from 2016 to 2018.

	2016	SD	2017	SD	2018	SD	2016 − 2018	SD
Weight (kg)	136	31	125	35	120	58	120	20
min	208		207		199		207	
mean	370		339		465		465	
max								
SFL (cm)	199	11	191	13	184	18	184	13
min	223		227		221		225	
mean	290		265		297		297	
max								
Age (years)	7	1.2	6	1.3	6	1.5	6	1.3
min	10		9.8		9.5		9.8	
mean	14		14		13		14	
max								

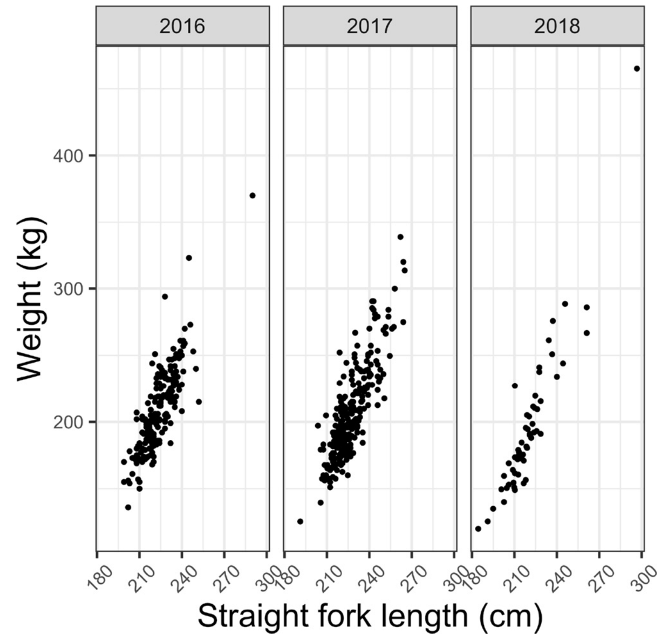

Fig. 1. Scatter plots showing the length/weight relationship of 508 Atlantic bluefin tunas (BFTs) caught inside the Norwegian Exclusive Economic Zone (EEZ) in 2016 (n = 201), 2017 (n = 248) and 2018 (n = 59).

Prey escaping BFT attacks included primarily juvenile mackerel, but also sprat (*Sprattus sprattus*), herring and garfish (*Belone belone*). Seventy-two observations had no available information about behavior.

The latitudinal positions of BFT observations made between 2016 and 2018 ranged from 57°44 N to 76°20 N, and nearly all observations were made near the Norwegian coastline (Fig. 5). More than 50 % of all observations made in recent years were of school sizes in the range of 1–5 individuals (Fig. 6).

A significant relationship between size of school versus Julian day of observation was found. School size was affected by time of the year (df = 2, Deviance = 11.19, Residual df = 182, Residual Deviance = 241.32, $p < 0.01$), with an optimum time of the year defined by a significant negative second-order polynomial ($z = 2.44$, $p < 0.01$). The probability of encountering schools > 10 individuals was highest between mid-September to mid-October (Fig. 7).

4. Discussion

Bluefin tuna has reestablished in Norway and is exhibiting its historical migration patterns in Norwegian waters in recent years, after being absent for decades. The comeback coincides with the overall annual increase in BFT spawning stock biomass (SSB) observed over the last decade and documented in both the Mediterranean Sea and in the Northeast Atlantic Ocean, during feeding and long-distance migration events (ICCAT, 2018, 2019). Mainly larger (120–465 kg) and mature (6–14 years) BFTs in good condition ($K > 1.5$), have been visiting the high latitudes of Norwegian coastal waters after the comeback. Fish sizes recorded in this study are equal to the sizes of BFTs that were present in Norwegian waters from 1960 to 1965 (Nøttestad and Graham, 2004; Nøttestad et al., 2017).

Historically, the oldest (12–15 years) and largest (> 150 kg) individuals arrived first and migrated further north along the Norwegian

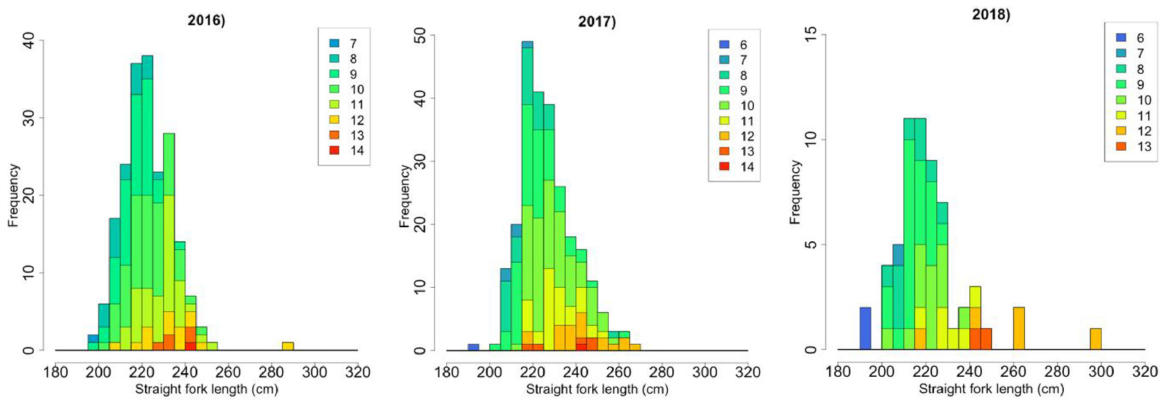

Fig. 2. Frequency of age at straight fork length (SFL) for Atlantic bluefin tunas (BFT) from 2016 to 2018, including all age-determined and all age-estimated BFTs. Each colour represents age in years, ranging from 6 to 14 years.

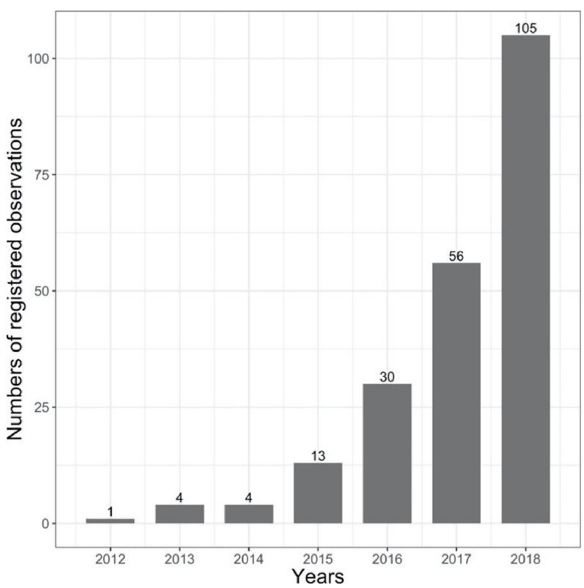

Fig. 3. Barplot showing count (number above each bar) of a total of 213 registered observations of Atlantic bluefin tuna (BFT) inside the Norwegian Exclusive Economic Zone (EEZ) over the years, from 2012 to 2018. Observations include commercial catches, bycatches, strandings, echo and sonar recordings and visual observations.

Table 4
Count of registered observations of Atlantic bluefin tuna (BFT) for each month from 2016 to 2018.

	2016	2017	2018
January	0	0	0
February	0	1	0
March	0	0	0
April	0	0	0
May	0	0	0
June	0	0	0
July	0	0	3
August	7	30	36
September	9	22	45
October	12	3	16
November	2	0	3
December	0	0	2
Total:	30	56	105

coastline (Hamre, 1962; Hamre and Tiews, 1964; Tangen, 1999). Druon et al. (2016) suggested that small juvenile BFTs (< 25 kg) do not tolerate low Sea Surface Temperatures (SSTs) as well as larger (> 25 kg) individuals who have a higher SST tolerance. This indicates that the size-dependent tolerance for wider ranges of SSTs may also apply throughout their life when they continue to grow even larger. Nøttestad et al. (1999) document that long-distance migrations of herring, mackerel and capelin are a function of fish length, and suggest that an increase in body size will determine an increase in the extent of migration for these species. This may also apply to the long-distance migration of BFT. Also, the increase in abundance (ICCAT, 2019) of this energy-demanding species may explain the expansion of its distribution towards northern productive waters, as the need to make long-distance migrations in search for available food resources is likely to increase with a growing population (Nøttestad et al., 2016a). BFT seems now to both arrive and leave later compared to between the 1950s and the 1970s, when the tuna stayed from early July until late October (Nøttestad et al., 2017). Historically smaller individuals (50–100 kg) arrived to and left Norwegian waters a few weeks later than the larger ones (Hamre, 1959, 1961, 1962). However, those small sized individuals have not been observed in Norwegian waters since the BFT comeback.

Seasonal variation in length/weight relationship has been documented for both juveniles and large adult BFTs, and it revealed that they grow rapidly during summertime and early autumn, and slower during the winter season (Mather et al., 1995; Fromentin and Powers, 2005; Rooker et al., 2007). This can be associated with spawning costs and feeding periods right after spawning (Chapman et al., 2011). A higher condition (K) in BFT can also occur as a result of energy being saved due to a missed spawning event (Jørgensen et al., 2006). The differences in BFT K observed in Norwegian waters between 2016 and 2018 could therefore be due to the amount of energy spent during spawning prior to migration to Norwegian feeding grounds, and to how much prey was available during the feeding season. These factors may also explain why our results show a higher condition (K) for BFT in Norwegian waters, compared to the condition (K) Percin and Akyol (2009) found for BFT in the Mediterranean Sea. The high condition may be linked to high food availability, as BFT migrate to Norwegian waters explicitly to feed on a vast amount of prey (Tangen, 1999; Trenkel et al., 2014; Nøttestad et al., 2017). It is difficult to compare the condition of BFT in recent years to previous periods (1950s to 1980s), as there is a lack of historical data on the condition (K) of BFTs that visited the Norwegian coast during those decades (Nøttestad and Graham, 2004; ICCAT, 2018).

A significant increase in the number of BFT observations was recorded in Norwegian waters from 2012 to 2018, coinciding with an increased SSB as well as with a more northern expansion of the fishing pattern for BFT in the Northeast Atlantic during the same period (2018 and 2019). In addition, the latitudinal distribution of observations has widened each year between 2016 and 2018, indicating a year by year increase in the latitudinal distribution of this species. The distribution

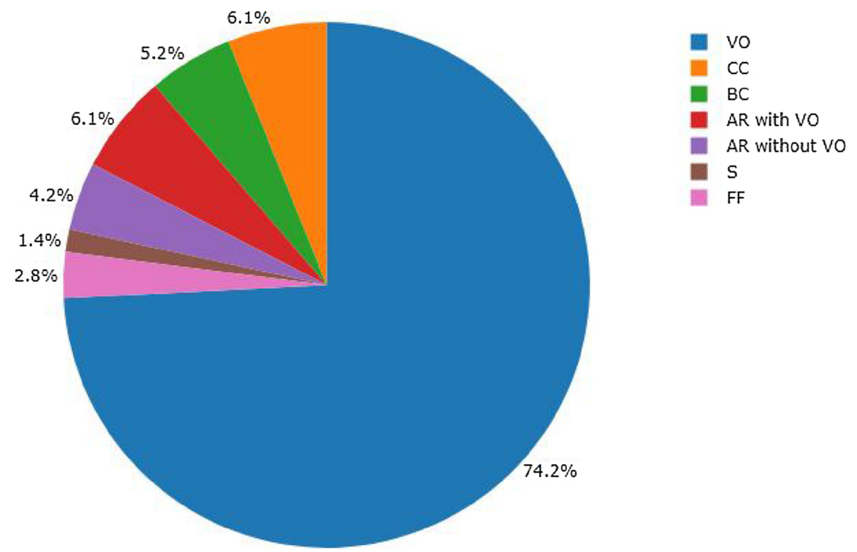

Fig. 4. Pie chart illustrating the different types of observations collected in this study: visual observations (VO), commercial catches (CC), bycatches (BC), acoustic recordings with visual confirmation (AR with VO), acoustic recordings without visual confirmation (AR without VO), strandings (S) and fish farms (FF).

range surpassed historically known ranges (Hamre, 1961), with the northernmost observation in history being registered so far at 76.2 °N, just south of Svalbard on September 29th, 2018, where the recorded sea temperature was just 3.5 °C. Atlantic bluefin tuna requires significant amounts of prey for the maintenance of growth and body temperature (Block and Stevens, 2001).

Most observations were visual observations of BFTs hunting and feeding at the surface. Individuals seemed to mainly prey on mackerel, which was confirmed by stomach content analysis and by sightings of juvenile mackerels escaping during BFT observations. Mackerel in the Northeast Atlantic have expanded their northern distribution in recent years (Nøttestad et al., 2016a, b), and as they are an important food-source for BFT, it is likely that the tunas follow mackerel's migration patterns and therefore expand their own northern distribution.

The number of BFTs observed in a limited area ranged from solitary individuals up to larger schools of > 100 individuals, with small schools (1–5 individuals) representing most observations (Fig. 6). It is worth mentioning that these observational counts are most probably conservative numbers, since an unknown number of BFT may have been present in an area without performing any surfacing behavior during hunting for schooling fish prey close to the surface. Up to an estimated 6000 individuals were observed hunting in several separate

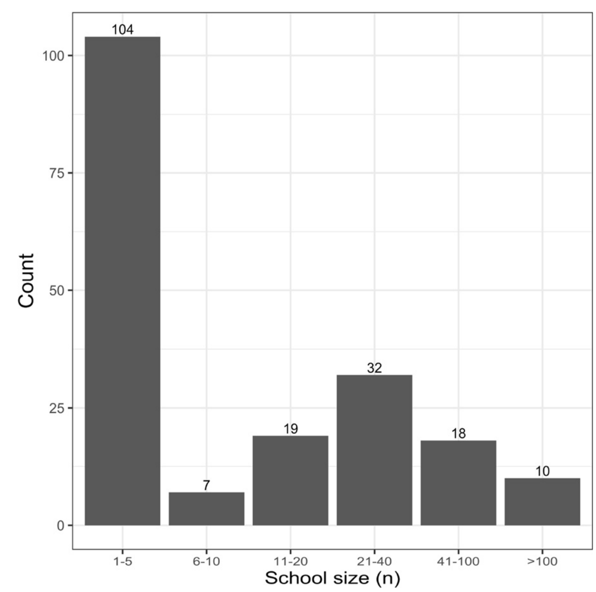

Fig. 6. Number of BFT school size categories observed from 2014-2018.

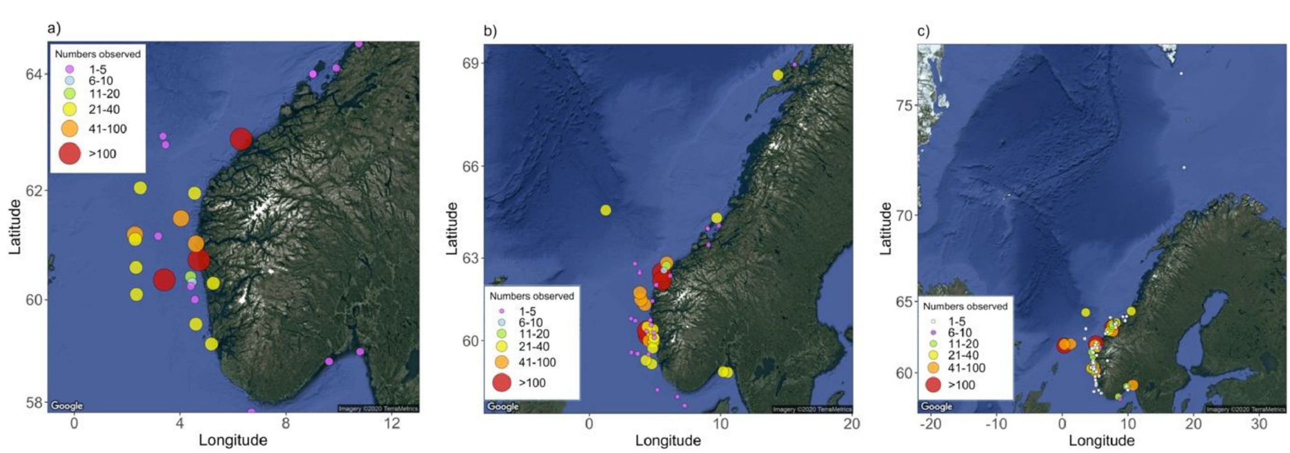

Fig. 5. a) Map of the Norwegian coast, with bubble plot of 29 observations of Atlantic bluefin tuna (BFT) observed in Norwegian waters during 2016; b) 53 observations of BFT in Norwegian waters during 2017; c) 100 observations of BFT in Norwegian waters during 2018. Colors and sizes of bubbles represent the approximate numbers per observation.

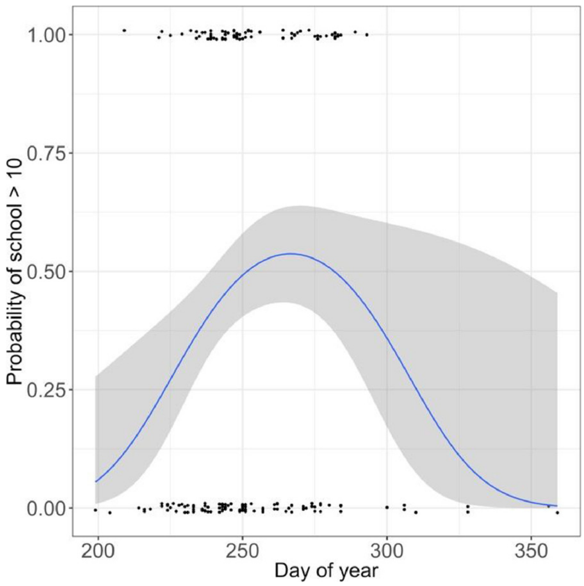

Fig. 7. Probability of encountering large school sizes (> 10 fish) of Atlantic bluefin tuna (BFT) by days of the year, where day 200 – 350 represent the start (July) and the end (December) of BFT's feeding season in Norwegian waters. The blue line represents the best model that includes a significant 2nd order polynomial. The shaded area represents the 95 % confidence interval for the model line.

schools within an area of approximately 10 square nautical miles, late in the season. The change in schooling behavior may be due to zooplankton species (abundant *Calanus* sp.) migrating to deeper waters during late autumn (Melle et al., 2004). Major zooplankton predators, such as mackerel and herring, reduce their feeding activity and organize themselves in larger schools with higher densities for increased protection (Nøttestad et al., 2004). Atlantic bluefin tuna may adjust their schooling behavior also regrouping into larger schools when their prey species establish larger schools during late autumn (Nøttestad et al., 2020). In addition, prey species such as juvenile and adult mackerel and herring, display advanced antipredator behavior including maneuverability, confusion and dilution effect when swimming in polarized schools (Parrish, 1993; Nøttestad et al., 2004, 2014). The change in BFT's schooling behavior throughout the feeding season could therefore be a result of readjustments to the changing behavior of their prey.

The small school sizes observed in Norwegian waters along with the dynamic behavior of BFT may negatively influence the catch rates and fishing capacity of the Norwegian BFT fishery (Nøttestad et al., 2020). The weather conditions in the Northeast Atlantic may also negatively impact the efficiency of fisheries, as fishermen mostly rely on visually observing BFT at the surface to locate schools. Also, fishing operations are more difficult to carry out in rough weather. Furthermore, BFT fishing has been missing for decades in Norway, which has led to a loss of valuable fisherman skills and knowledge over the years, rendering today's attempts at restarting BFT fishing activities even more challenging.

More studies on abundance, distribution and general biology in relation to catch sizes, individual sizes and ages are needed. Multibeam sonar recordings are a useful fishery-independent tool for providing indices of BFT abundance (Melvin, 2016; Uranga et al., 2017). Because of their ability to monitor and quantify high volumes of data at relatively low costs, (Uranga et al., 2017), multibeam sonars in combination with visual methods, represent useful tools to obtain BFT abundance estimates in Norwegian waters. Using pop-up satellite tags is a good method to measure BFT migration patterns, along with experienced sea temperatures at different depths (Block et al., 1998). To date, only one individual has been tagged successfully with a pop-up satellite tag in Norwegian waters and delivered information on migration (Ferter et al., 2018). However, more BFT tagging is needed especially in the northernmost feeding areas in the Northeast Atlantic Ocean to collect more information within and outside Norwegian waters.

Credit authorship contribution statement

Leif Nøttestad: Conceptualization, acquisition, Investigation, Methodology, Project administration, Funding, Resources, Supervision, Validation, Writing - review & editing. Erling Boge: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. Keno Ferter: Conceptualization, Methodology, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105689.

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