The return of the Atlantic bluefin tuna to Norwegian waters

Master thesis in Fisheries Biology and Management

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Photograph front page by Enrico Wyrwa

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Abstract

From 1950 to 1964, Norway was one of the largest fishing nations in the Northeast Atlantic, annually targeting and harvesting up to 15 000 tons of Atlantic bluefin tuna (ABFT) (*Thunnus thynnus*). During the 1970's, the ABFT gradually disappeared from high latitudes along the coast of Norway, and was nearly completely absent by the mid-1980's. After several decades of absence, we now witness, based on observations and catch data from 2012 and onwards, that the ABFT has started to revisit Norwegian waters. This study explores the overall development and distribution in space and time, biology and ecology of the ABFT´s return to Norwegian waters. This was done by analyzing the Norwegian commercial catch and bycatch data including biological data on weight, length and age of ABFT from 2016 to 2018. Information and observations of ABFT from inside the Norwegian Exclusive Economic Zone during recent years were also collected from various sources, to be systematized and then analyzed. The types of observations collected were visual sightings, sonar and echo-sounder recordings, commercial catches, bycatches, strandings of dead ABFT and observations of tunas getting trapped inside fish farms. This study shows that predominantly larger (overall range in catches: 120-465 kg in weight and 184-297 cm in straight fork length (SFL)) individuals of adult ABFT between 6 and 14 years of age, have started to revisit the coast of Norway. No statistical difference in mean weight between years was found ($p = 0.23$). Mean SFL was significantly longer in 2017 than in 2016 ($p < 0.01$) and 2018 ($p < 0.01$) (227 cm vs. 223 cm and 221 cm, respectively. Moreover, a significant difference in mean age of ABFT in 2018 and 2016 was found (9.5 years and 10 years, respectively; $p < 0.05$). Numerous new observations of ABFT in Norwegian waters were retrieved in this study, where a significant increase in observations from 2012 ($n = 1$) to 2018 ($n = 105$) was found ($p < 0.01$). Most observations were visual sightings of ABFT schools jumping and hunting at the surface. Numbers of ABFT per observation ranged from single solitary individuals up to very large schools of approximately 1000 individuals, and in one area, there were a total of approximately 6000 individuals spread out in several schools within roughly 10 nautical miles. Most observations reported and used in this study were made between mid-July and until mid-October each year, whereas a few observations were made in November and December. The northernmost registered observation throughout history was reported in September 2018 at 76.2°N, just south of Svalbard. Moreover, a school of ABFTs was observed in Vesterålen, Lofoten during February 2017. This suggests that some ABFT are now extending their seasonal feeding migration and may even overwinter from November to February in Norwegian waters prior to spawning. With an increasing rate of return into Norwegian waters and an increase in stock size, the data strongly indicates that ABFTs are reestablishing their historic feeding migration routes in this area. An abundance increase of ABFT in Norwegian waters is likely to impact prey abundance, increase the risk of ABFT bycatches and increase the risk of ABFT penetrating through fish farm nets. Furthermore, because of the abundance increase, the historical Norwegian ABFT fishery has been reestablished, and is likely to increase in the coming years. To expand our knowledge of the return of ABFT into Norwegian waters, more studies on abundance, biology and ecology of the population should be conducted, including systematic multibeam sonar recordings and satellite tagging projects.

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LIST OF ABBREVIATIONS

ABFT = Atlantic bluefin tuna

CFL = Curved fork length

EEZ = Exclusive Economic Zone

ICCAT = International Commission for the Conservation of Atlantic Tunas

IMR = Institute of Marine Research

RSS = Residual sum of squares

RWT = Round weight

SCRS = Standing Committee of Research and Statistics

SFL = Straight fork length

SSB = Spawning stock biomass

1. Introduction

1.1 Phylogeny, biology and natural distribution

The Atlantic bluefin tuna (*Thunnus thynnus)*, hereafter ABFT, is part of the mackerel family (*Scombridae*) and is the largest of the tuna species in the world (Block and Stevens, 2001). There is a total of 15 species of tuna that together comprises the *Thunnini* tribe, a subgroup of the Scombridae family (Collette et al., 2001). The ABFT can reach a life span of up to 40 years and can reach sizes of more than 3 meters in length and weigh more than 700 kg (Cort et al., 2013; ICCAT, 2018). The ABFT is a highly migratory species and has the widest geographical distribution of all tuna species. It inhabits the pelagic waters of the entire Atlantic Ocean and can dive to depths of more than 1000 meters (Fromentin and Powers, 2005). ABFTs can also maintain body temperature to remain up to 7 °C above surrounding water temperature (Block et al., 2001; Block and Stevens, 2001), which allows them to feed actively in colder waters without significant reduction of body temperature (Fromentin and Powers, 2005). High body temperatures in tunas is thought to be associated with the evolution of high swimming speed (Carey et al., 1971). The ABFT may reach maximum burst speeds of approximately 80km h^{-1} (Wardle et al., 1989) and is capable of maintaining high cruising speeds over long durations of time (Stevens and Carey, 1981). ABFTs display similar traits with cold-water species such as larger size, longer lifespan, shorter spawning season and later maturity than tropical tunas (Fromentin and Fonteneau, 2001).

The ABFT grows slower than tropical tunas (Fromentin and Fonteneau, 2001) but is still considered to have a very rapid growth rate for a teleost fish, especially through juvenile stages when it grows approximately 30 cm per year (Fromentin and Powers, 2005). With rapid growth and high metabolic rate, where it spends a lot of energy maintaining relatively high body temperature, ABFT must eat a significant amount of prey. An adult individual may consume large quantities of prey and gain up to 50-70 kg in weight during a feeding season, depending on size (Nøttestad et al., 2017a).

The regenerative ability of a population, which is crucial information for determining commercial viability of a stock, is largely determined by the characteristics of reproduction, growth and mortality (Quinn and Deriso, 1999). The reproductive biology of the ABFT is not well known and therefore the spawning potential of the species is not fully understood (Block and Stevens, 2001; Fromentin and Powers, 2005). However, like most fish, tunas are oviparous. They are considered batch spawners (Block and Stevens, 2001), meaning they mature new spawning batches continuously throughout the reproductive season in which they spawn several times (Hunter et al., 1985). Fertilization of eggs occurs in open water where they release their gametes (Block and Stevens, 2001). There are numerous spawning patterns within the *Thunnus* genus. The spawning pattern of the ABFT is migratory and spatiotemporally confined and is shared by other tuna species; e.g. *Thunnus orientalis*, *Thunnus alalunga* and *Thunnus maccoyii* (Block and Stevens, 2001). Since the early 1980's, management of ABFT considers two stocks separated at the 45°W meridian. The division was based on the recognition of two main spawning grounds, the West Atlantic stock that spawns in the Gulf of Mexico and the East Atlantic stock that spawns in the Mediterranean Sea (Fromentin and Powers, 2005), even though mixing between the two stocks has been shown (Block et al., 2005; Rooker et al., 2014). East ABFT matures earlier (4-5 years of age and < 45 kg) than the West ABFT (8-10 years of age and > 135kg) (Clay, 1991; Nemerson et al., 2000; Block and Stevens, 2001).

1.2 Historical fishing and migration pattern in Norway

Historically, the ABFT visited Norwegian waters from early July and until late October to feed (Nøttestad and Graham, 2004). ABFTs visiting the Norwegian coast during the 1950's and 1960's originated mostly from the Mediterranean Sea. There they spawned and started their extensive migration route to several places in the Atlantic Ocean, one of them being at high latitudes along the coast of Norway. During the feeding season (July to October), mainly adult individuals with sizes ranging from 50-520 kg visited the Norwegian coast (Hamre, 1962; Aloncle et al., 1972; Nøttestad and Graham, 2004; Nøttestad et al., 2017b). The migration pattern of the ABFT differed between sizes and composition of ages in the different schools. It was normal for the ABFT to arrive at Stadt at the start of the season, at approximately 62°N where the oldest (12-15 years) and largest individuals (> 100kg) arrived first in Norwegian waters (Nøttestad and Graham, 2004). These individuals migrated furthest to the north along the Norwegian coastline (Hamre, 1962; Hamre and Tiews, 1964; Tangen, 1999), and some were observed as far north as Laksefjord in Finnmark county (Hamre, 1957). At the end of the intensive feeding season, the largest individuals were also the first to leave the Norwegian feeding areas. Younger (5-12 years) and smaller individuals (50-100kg) arrived some weeks later and continued southwards of 62°N. They also left some weeks later than the largest individuals, from the coast (Hamre, 1957; 1959; 1961; 1962). ABFT has probably been feeding along the Norwegian coastline for thousands of years (Tangen, 1999; Nøttestad et al., 2017a), due to the high abundance of nutrient rich schooling prey like mackerel (*Scomber scombrus*), herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), sprat (*Sprattus sprattus)*, haddock *(Melanogrammus aeglefinus)*, lesser sandeel *(Ammodytes marinus)* and capelin (*Mallotus villosus*) (Tangen, 1999; Nøttestad et al., 2017b). During the 1950's and until the 1970's, lesser sand eel was probably the most important source of food for ABFT along the western coast of Norway (Cort and Nøttestad, 2007; Tangen et al., 2016). Increasing school-sizes of prey can lead to an increase in number of predators hunting them (Nøttestad et al., 2002). It is well-known amongst fishermen in Norway that the ABFT historically formed larger schools towards the end of their feeding season (October) as a result of the mackerel forming larger schools.

From 1950 to 1964, Norway had one of the largest fishing fleets targeting ABFT in the Northeast Atlantic (Nøttestad and Graham, 2004). Nearly 470 purse seine-vessels participated in the fishery along the Norwegian coastline, ranging from the Oslofjord in the south, up to Troms county in the north (Tangen, 1999). Close to 15 000 metric tons of ABFT could be caught within a single fishing season (Hamre and Tiews, 1964; Nøttestad and Graham, 2004; Nøttestad and Graham, 2005; ICCAT, 2016) (Figure 1).

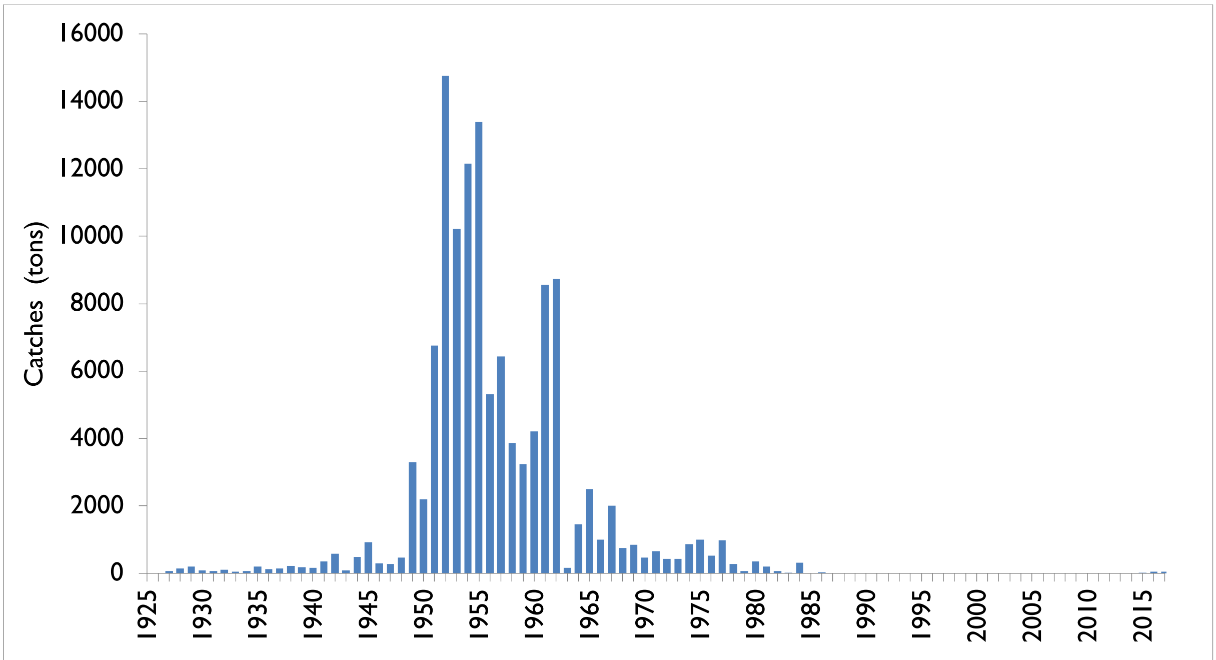

Figure 1: *ABFT catch taken in Norwegian waters from 1925 to 2016. Retrieved from Nøttestad et al. (2017a).*

The earliest registered catches of ABFT by purse seine (Figure 2) in Norway were already back in 1926 (Tangen, 1999). Harpoons, longlines, beach seines and trolling lines were also used to catch ABFT in Norwegian waters (MacKenzie and Myers, 2007; Nøttestad, 2017).

Figure 2: *Picture illustrating the Norwegian fishery with purse seine vessels used during 1950's to 1970's. A large ABFT is being lifted up on the deck of M/S "Radio". Photo: M/S "Bluefin" / Atle Nekkøy.*

The Norwegian commercial fishery targeting ABFT began in the 1940's and lasted until late 1970's, when the ABFT gradually disappeared from high latitudes along the coast of Norway and were practically nowhere to be seen in Norwegian waters by the mid-1980's and onwards (Nøttestad et al., 2017b).

1.3 Possible reasons for disappearance of ABFT in northern waters

For decades, the ABFT has been absent from Norwegian and Nordic waters, and the reasons for this are uncertain (MacKenzie and Myers, 2007). Limited stock size seems to be one major reason for the decline of ABFT in Norwegian waters historically (Figure 3), whereas increased stock size (ICCAT, 2018), is probably a main reason for the presence of ABFT in Norwegian waters from about 2013 onwards (Nøttestad et al., 2017b).

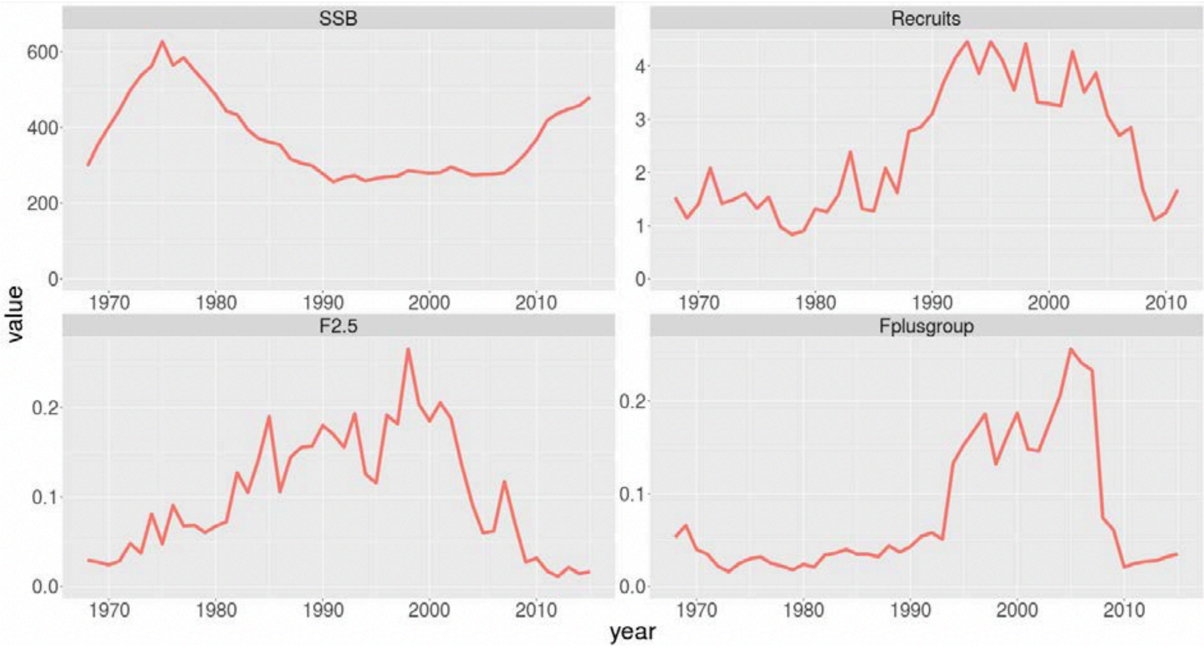

Figure 3: *Spawning stock biomass (SSB) (in thousand metric ton), recruitment (in million), and fishing mortality (average over ages 2 to 5, and 10+) estimates from the 2017 stock assessment. Retrieved from ICCAT (2018).*

Studies indicate that recruitment overfishing (harvesting on SSB to the point where recruitment is affected (Jennings et al., 2009)) as well as growth overfishing (harvesting individuals before they have a chance to reach their growth potential (Jennings et al., 2009)) on juvenile ABFT around spawning areas in the Mediterranean Sea during the 1950's and 1960's, and in the Bay of Biscay and off the coast of western Africa during the 1960's and onwards, were the main contributors to the decline of the East Atlantic stock (Cort and Nøttestad, 2007; Cort and Abaunza, 2015; Cort and Abaunza, 2016; Cort, 2017; Nøttestad et al., 2017a; Nøttestad et al., 2017b; ICCAT, 2018). Altogether, it is likely that ABFT migration patterns have been affected by interactions between environmental, trophic and fishing processes (Fromentin, 2009).

1.4 Return of ABFT to Norwegian waters

In 2013, observations of schools of ABFTs were made in Bulandet, Sogn og Fjordane county, along the southwestern coast of Norway. Since 2013, an increasing number of observations of ABFT have been recorded along the Norwegian coast (Nøttestad et al., 2017b), suggesting that some ABFT now extend their migration to historically prevalent feeding habitats and stay along the coast of Norway from July to October. A large school of ABFT was observed exhibiting feeding behavior even as far north as Vesterålen in February 2017 (Nøttestad et al., 2017b). This suggests that schools of ABFT may overwinter from November to February in Norwegian waters prior to spawning. Catch data from the Norwegian commercial fleet during recent years show that predominantly larger (> 150 kg) individuals of adult ABFT have started to revisit the coast of western Norway after several decades of absence (Nøttestad et al., 2017b). This is a similar pattern to the 1950's and 1960's, where these adult size-groups were observed along the northern part of the Norwegian coastline (Cort and Nøttestad, 2007).

Ever since new observations of ABFT were registered in Norwegian waters in 2013, the Institute of Marine Research (IMR) in Bergen has taken multiple genetic samples of individual ABFT. The major aim has been to pinpoint from what spawning grounds (origin) the different individuals that visit the Norwegian coast originate from. In 2016, IMR contributed with about 200 genetic samples to the International Commission for the Conservation of Atlantic Tunas (ICCAT), and more than 250 genetic samples were taken in 2017. Genetic analysis showed that there is indeed a mixture between the stocks (Rodríguez-Ezpeleta et al., 2017). Approximately 90% of ABFTs caught along the Norwegian coast during 2016 and 2017 came from spawning grounds in the Mediterranean, and about 3% came from spawning areas along the Gulf of Mexico. The remaining 7% could not be assigned to either spawning ground and may belong to other unknown spawning areas (Aranda et al., 2013; Nøttestad et al., 2017b; Rodríguez-Ezpeleta et al., 2017).

During the last 10 years, the East Atlantic stock has shown a significant increase in stock size whereas the Western Atlantic stock has not shown any improvement (ICCAT, 2016; 2017; 2018; Nøttestad et al., 2017b). Even though Norway was given ABFT quotas from ICCAT in 2007, Norwegian authorities chose to set the national quota aside for conservation purposes, due to massive overfishing in the past, and great uncertainty regarding stock size and status on abundance (Nøttestad et al., 2017a). Norway decided to open for a trial-fishery for ABFT inside the Norwegian Exclusive Economic Zone (EEZ) in 2014 and 2015. This was due to scientific documentation giving repeated annual evidence of a positive development and increased stock size. There were also longline catches from an Icelandic longline vessel of large adult ABFT off Iceland in 2012 and 2014 (MacKenzie et al., 2014; Nøttestad, 2017), indicating a broader expansion of ABFTs in northern waters in recent years. Targeted annual quotas was given by the Norwegian Directorate of Fisheries from 2016 to 2018. On September 16th, 2016, the purse-seine vessel M/S "Hillersøy" managed to catch 191 individuals, averaging at over 200 kg per individual, in one single purse-seine catch

(Nøttestad, 2017; Nøttestad et al., 2017b). In 2017, the purse-seiner M/S “Bluefin” caught 234 individuals and in 2018, the Norwegian Ministry of Trade, Industry and Fisheries decided that two Norwegian purse seine vessels were allowed to fish for ABFT (M/S “Hillersøy” and M/S “Salvøy”), who together caught 56 individuals. During a satellite tagging project from August 24th to September 30th, 2018, two ABFTs were caught on angling gear (Ferter et al., 2018).

1.5 Knowledge gaps, present available data and study objectives

There are a lot of questions regarding the recent return of the ABFT to Norwegian waters and a lot of basic information we do not presently have. Knowledge of how many ABFTs that are visiting the Norwegian coast during a feeding season, their size and age, their school sizes and size distribution along the Norwegian coastline, are mostly lacking. Also, little is known about the duration of their stay and what they are feeding on while they visit Norwegian waters and whether they form larger schools towards the end of their feeding season. The condition and length/weight relationship of ABFTs visiting Norwegian waters is also unknown. Condition is a proxy of fitness in fish (Adams and McLean, 1985; Booth and Keast, 1986) and could therefore give direct insight to how favorable the feeding conditions have been for ABFTs during recent years in Norwegian waters. The condition is normally estimated based on the length/weight relationship of a fish which is generally assumed to be in better condition with heavier weight of a given length (Bolger and Connolly, 1989). In this study, I explore these unanswered questions and attempt to increase our knowledge around the return of the ABFT to Norwegian waters.

With an increasing number of observations made each year from 2012 and onwards, it was likely that people living near the coast, and especially fishermen, had unregistered observations of ABFT and were sitting on otherwise useful information. Engaging citizens in science has shown to be an important tool for ecological research (Dickinson et al., 2012), and by engaging people along the coast of Norway in registering their observations, it could provide important information on the abundance, migration pattern, distribution and ecology of ABFT in Norwegian waters. Due to limitation in time and resources, it was impossible to collect information of all potential observations that had been made recent years without engaging citizens in reporting their observations.

It is well-established knowledge by Norwegian fisherman that targeting smaller schools of ABFT, secure better meat quality as the ABFT get less stressed when they are caught in fewer numbers per purse-seine catch. Therefore, to ensure best meat quality, it was important to explore if school-size was related to time of year, and if so, use that information to determine the best time to fish for it.

Rise in sea temperatures is often suggested as a driving factor for the recent return of ABFT into Norwegian waters. The likely ranges in temperature that the ABFTs have experienced when migrating to Norwegian waters from 1940 to 2018 is not known. Based on sea temperature data from 2018 all the way back to 1940, which are available at the oceanographic department at IMR, the likely experienced temperature ranges for ABFT were explored.

My objectives were as follows:

General objective: Obtain insights into the biology, distribution and ecology of ABFTs in Norwegian waters, in space and time, during recent years with a main focus on the last three years (2016 to 2018).

Specific objectives:

1) Determine basic biological parameters such as the size (weight and length), condition and age of ABFTs that were caught along the Norwegian coast and more offshore areas inside the Norwegian EEZ from 2016 to 2018.
2) Investigate relationships between size of individual ABFT to latitude of distribution.
3) Compare the size range of ABFTs that visits Norway at present compared to historically known size ranges.
4) Obtain new observational data (visual and acoustic) in space and time of ABFT in Norwegian waters in newer times, and map the likely distribution of ABFT in Norwegian waters within recent years (2016 to 2018).
5) Investigate relationships between size of schools of ABFT to time of year.
6) Discuss water temperatures likely to have been experienced by ABFTs in recent years and compare to previous years.

2. Materials & Methods

2.1 Capture data from the fishery

The data used for various analyses in this study, was collected from commercial catch statistics at the Norwegian Directorate of Fisheries and ICCAT, as well as from a whole range of obtained and structured data on observations of ABFT from various sources. As there were lack of standardization in methods used for treatment of fish prior to weighing, between the certified fishing vessels, and with different methods for measuring length of ABFT caught, the biological data was converted to standardize it for further comparison analysis. Conversions of ABFT weights were already performed by IMR staff before this study started. Conversion factors used for weight can be found in Appendix A. All length measurements from ABFT caught by the commercial fishery in 2017 and 2018 were measured as Curved fork length (CFL) and bycatches as Straight fork length (SFL). However, in 2016 all individuals of ABFT both from the commercial catches and of bycatches, were measured as SFL. All CFL measurements were converted to SFL using Equation A. Since it was likely that the age determination for 2018 would not be ready before this thesis was due, the age distribution for 2018 was estimated based on an age-length key made from already age-determined individuals of ABFT from 2016 and 2017 (Table 1).

$$SFL = 0.9596 \times CFL + 2.0985$$

Equation A: *Formula for converting CFL to SFL, where CFL = Curved Fork Length and SFL = Straight Fork Length. Retrieved from Lombardo et al. (2017).*

The following biological measurements, were performed by technicians at IMR:

- Straight fork length (SFL): The length from the snout to the fork of the caudal fin.
- Curved fork length (CFL): The length from the snout to the fork of the caudal fin, corresponding to the fish curvature.
- Round weight (RWT): The complete weight of the entire fish just as it comes out of the water, before any processing or dressing.
- Sample of first dorsal spine from each individual ABFT for age determination.

Descriptions for SFL, CFL and RWT were retrieved from Lombardo et al. (2016). All measurements were standardized to centimeters (cm) for length and kilograms (kg) for weight.

2.1.1 Biological measurements 2016 to 2018

2016

The biological measurements of ABFT were taken from a total of 191 ABFT caught by the licensed fishing vessel M/S “Hillersøy” in 2016. This was done directly onboard the fishing vessel and on shore at the fish landing factory “Pelagia” in Florø. Biological measurements were also sampled from 10 bycatches in 2016. The conversion factor used for weight was 1.16: “Gutted with head, gills are removed” (Appendix A, Table I).

2017

The biological measurements of ABFT were taken from a total of 234 ABFT caught by the licensed fishing vessel, M/S “Bluefin” in 2017. This was done directly on board the fishing vessel and on shore at the fish landing factory “Pelagia” in Florø. Biological measurements were also sampled from 14 bycatches in 2017. The conversion factor used for weight was 1.28: “Gutted without head” (Appendix A, Table I).

2018

The biological measurements of ABFT were taken from a total of 56 ABFT caught by the two licensed fishing vessels, M/S “Salvøy” and M/S “Hillersøy” in 2018. Measurements were done directly on board the fishing vessels and on shore at the fish landing factory “Skude fryseri” in Skudeneshavn. Biological measurements were also sampled from 5 bycatches in 2018. The conversion factor used for weight was 1.17; “Gutted with head but removal of operculum” (Appendix A, Table I). On M/S “Hillersøy”, no conversion factor for weight was used.

2.1.2 Length/weight relationship and condition

The length/weight relationship of ABFT caught between 2016 and 2018 was expressed using Equation B.

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

Equation B: *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. When β = 3, the increase in weight is isometric. When β is anything but 3 then the growth is allometric. If $\beta > 3$ it is positive allometric and is $\beta < 3$ it is negative allometric (Edwards, 1984; Beverton and Holt, 1996; Draper and Smith, 2014).*

The logarithm of this equation was used to obtain a linear regression model and β was estimated.

Condition of each ABFT caught between 2016 and 2018 was estimated with Fulton's Condition Factor (K) (Ricker, 1975) (Equation C).

$$K = 10^5 \times RWT/FL^3$$

Equation C: *Where K = Condition, RWT = Round Weight in kg and FL = Fork Length in cm.*

2.1.3 Age

The ages of almost every individual ABFT (n = 416) caught in the directed fishery or as bycatch inside the Norwegian EEZ between 2016 and 2017 were age-determined by Arrizabalaga et al. (2019), based on the first dorsal fin spine of every ABFT. Fin spines were collected by technicians from IMR. Each consecutive year, from 2016 to 2018, the samples were sent to AZTI Technalia for age determination, where fin spine sampling and sectioning procedures were performed as described by Rodríguez-Marín et al. (2012) and Luque et al. (2014). Procedures for examination, age determinations and interpretations of fin spines were performed following the procedures described by Luque et al. (2014).

There were no age-determined individuals available from 2018 in this study. Therefore, for all fish caught in the directed commercial fishery (n = 56) and from bycatches (n = 3) that had been length measured during 2018, the age was estimated. In addition, for a total of 33 individuals of unaged ABFT from catches and bycatches during 2016 (n = 11) and 2017 (n = 22), the age was estimated. Age estimations of unaged ABFT were conducted with the FSA r-package (Ver. 0.8.22.9000) (Ogle et al., 2018) in R-statistical software (R Development Core Team, 2013), and based on the summary of the age-length key made from the age-determined individuals from 2016 and 2017 (Table 1). A semi-random method was used, where it is random which fish that get assigned to which age, but primarily not random how many fish that gets assigned to each age. However, since the FSA r-package, only accepted minimum SFL values from 2018 to be equal to or above the minimum value for SFL from the age-length key from 2016 and 2017 (191 cm) when estimating ages for 2018, for one ABFT with a SFL 184 cm, the age could not be estimated.

Table 1: *Age-length key made from age-determined individual ABFT from 2016 and 2017, where SFL is divided into 5cm categories with numbers for count of ABFT per age (6-14 years) to each length category. Age analysis was based on the first dorsal spine from each individual that was age-determined by Rodríguez-Marín et al. (2012).*

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**

<u>2.2 Observational data</u>

2.2.1 Procedures for collecting observations

As many observations of ABFT as possible from inside the Norwegian EEZ were needed to collect a representable amount of data over the magnitude and distribution in space and time during present and previous years. Observations of ABFT made in recent years, were collected from several sources and through several different platforms of communication, such as social media (Facebook), various news magazines, the commercial fishing fleet and the Norwegian reference fleet, using an online observational form which was made in collaboration with IMR specifically for this project (Appendix B). The process of sending out information about this project to the public, started in early August 2018 before the ABFTs were thought to arrive to their seasonal feeding grounds in Norwegian waters. This was to ensure that as many people as possible were prepared to register observations if they observed ABFT during 2018, and from early on start the process of registering observations made during earlier years. Documentation of observations of ABFT from footages such as pictures or videos (surface and underwater) were of particular interest to collect, as these were good scientific data to validate reported observations. All information and every observation collected in this study was systemized in Microsoft Excel software. Example pictures of sonar and echo-sounder recordings of what were likely to be of schools of ABFT in the Norwegian Sea in recent years, can be found in Appendix E.

Social media

A questionnaire (Appendix C) with several questions regarding observations of ABFT that people might have done in recent years was designed. The questionnaire was distributed on different Facebook forums and groups. The members of these forums and groups were asked to send in their observations to IMR/me, preferably with pictures and videos to validate their observations. Information on numbers of ABFTs seen, sizes of schools and individuals and behavior of the fish, was asked for to get a better understanding of the distribution of the different sizes of ABFT and how they behave while they are feeding along the coast of Norway. People were also encouraged to keep an eye out for ABFTs from August to October in 2018 and to report these observations. The Facebook groups and forums contacted were "Fridykkerforumet" at July 23rd, "Tunfisk Norge" at July 24th, and "Havfiske Norge" at August 15th. These were all groups where a large part of the members spends a fair amount of time at sea throughout the year and could, therefore, be more likely to observe ABFT. The group members that had made observations in previous years and in 2018 could either send their information on mail to erling.boge@hi.no, call as instructed or answer publicly on the different Facebook forums for others to see.

IMR

IMR published a news article in collaboration with this project on August 17th, 2018

(Lorentzen, 2018). This article contained the online observational registration form (Appendix B) for people to fill out if they had seen any ABFTs during the present or previous years. Participants could easily access the online observational registration form by clicking on a link found in the article. After someone had submitted an observation via the form, it was directly sent to the emails of those in charge of working with and registering the incoming observations. The online observational form was also sent out to the Facebook groups previously mentioned to make it easier for people to register their observations. The online observational form was used as the main tool for registering and retrieving observations further on during this study.

Fishing fleet

As commercial fishermen spend a great deal of their time at sea further out from the coastline, it was necessary to obtain any possible existing observations from the commercial fishing fleet that had previously not been collected and systematized. Sonar recordings and other non-visual observational data of ABFT were important to retrieve, especially from commercial fishing vessels as they were more likely to sit on this kind of data.

Different attempts to get the attention of commercial fishermen in Norway were made. The fishery-related newspaper "Fiskeribladet" published an article about this project on August 21st, 2018 (Martinussen, 2018a). The article contained descriptions about this project and the online observational form. This article made it possible to reach out to more people and fishermen spending a lot of time out at sea, and who were more likely to have seen ABFT during previous years. The fishing vessels that were given ABFT quotas from 2016 to 2018 amongst other various commercial fishermen were also contacted directly by mail, telephone and through personal meetings.

Observations were also registered from the commercial catches in the targeted fishery from 2016 to 2018. Each attempt to catch ABFT with purse seine (except when testing the nets before the season) and each catch of ABFT was registered as an observation. If no additional information was given about how many ABFT were observed when attempting to catch ABFT or when catches were made, 1-6 individuals for attempts and the exact number of ABFT caught in each catch, was registered as numbers observed.

Reference fleet

A presentation of this project was given for the Norwegian oceangoing reference fleet at their annual meeting held by IMR on October 25th, 2018 (IMR, 2019). The reference fleet consists of commercial fishermen targeting mackerel, herring, blue whiting, capelin and many more fish species. They were encouraged to send in their observations either by mail, telephone or via the online observational form. They were also asked to keep an eye out for more observations of ABFT in the future and to register these. In addition, they were asked to be on the lookout for any existing unregistered observations that they either knew about or that they might come across. The fishermen who had unregistered observations or otherwise useful information were asked to provide their contact information. The online observational registration form was then sent by mail to the fishers that had provided their contact information, for them to fill out.

Fish farms

ABFT have been known to occasionally get caught in fish farms in Norway, based on experience from past years (Nøttestad et al., 2017b). Knowing that a few ABFT already had been penetrating into fish farms during 2016 and 2017, it was necessary to get in contact with people working on or near fish farms and get them to register any potential observations of ABFT either as bycatch of ABFTs caught inside the fish farm pens, or of ABFT seen in the area near the fish farms. An article very similar to the one in Fiskeribladet also containing the online observational form to fill out, was posted by IntraFish on September 9th, 2018 (Martinussen, 2018b). IntraFish and Fiskeribladet are both publications of a company called IntraFish Media which is the world's largest provider of seafood news and information (Intrafish, 2019). IntraFish is a popular news magazine for many workers within or in relation to the aquaculture industry in Norway.

Hooked magazine

The recreational fishing magazine Hooked posted an article about this project at www.hooked.no on September 4th, 2018 (Hopland, 2018). Hooked magazine is a very popular sports fishing and hunting magazine which in 2017 had 1.1 million distinct readers from all over the country. This makes Hooked Norway's largest online sports fishing and hunting media. This was also a way to raise awareness into the public and thereby increase the number of observations of ABFT along the coast of Norway.

Searching the internet for unregistered observations

Effort was also put into searching through local online newspapers from all along the coast for any unregistered observations of ABFTs during previous years. All bycatches found were registered as observations. Any news cases about ABFT would then potentially show up. The group "Tunfisk Norge" on Facebook was particularly interesting to look through as this is a group where members post ABFT-related topics as well as observations they have made. The Facebook group "Havfiske Norge" was also searched through, as this group contains active recreational fishermen which spend a lot of time at sea. Observations were searched for by typing "Makrellstørje" in the search-engine for each newspaper-website and in the Facebook forums. www.google.no was also used as a broader search-engine to look for unregistered observations of ABFT in Norwegian waters recent years.

Satellite tagging project

A satellite-tagging project took place in the Bergen area, and consisted of nine teams of volunteer anglers with their own fishing boats, along with a research vessel from IMR. During this project from August 24th to September 30th, 2018, every observation of ABFT made by any of the participating fishing boats was registered in a logbook by the researchers, to be used for this study, with date, position, time of day, numbers of ABFT observed, approximate size and behavior, at best of ability.

2.2.2 Procedures for systemizing observations and assumptions for observations with missing information

Most observations that were registered either contained the detailed position with coordinates or with the name of the approximate area where the observations were made. If an observation only had the name of the area described without the exact position, www.googlemaps.com or www.gulesider.no was used to find the name and coordinates for that specific or approximate area which was given. Since R-statistical software required positions to be in Decimal Degrees (DD) format, they were registered as such. Many of the positions registered for the different observations were sent to me in Degrees/Minutes/Seconds (DMS) format. These were converted to Decimal Degrees using Equation D.

$$DD = \left(\frac{Seconds}{3600}\right) + \left(\frac{Minutes}{60}\right) + Degrees$$

Equation D: *Formula for converting Degrees °Minutes ' Seconds" (DMS) to Decimal °Degrees (DD).*

Observations that were made on days with calm winds likely to be under 6 m/s and waves no bigger than 2 meters, were classified as observations in “Good weather conditions”. Observations made on days with winds exceeding 6 m/s and waves above 2 meters, were classified as observations in “Bad weather conditions”.

If observations that were sent in for registration were missing important information that was needed for further analysis, these were the following assumptions and corrections that were made for each scenario;

- Completely missing any sort of position of observation = Not plotted on bubble plot map but included in total count of observations.
- Lacking information on exact date of observation = Only excluded from further analysis that required the exact date.
- No information on numbers observed = Registered as “1-6” individuals observed as a conservative approach.
- Lacking information on type of observation = Registered as “visual” observation.

Observations that had position, date, numbers observed and type of observation but were missing information on time of observation, weather conditions, approximate weight or length of ABFT observed, behavior of ABFT observed or additional information regarding the observation, could still be used in further analysis. In cases where observers explained that they observed ABFT throughout the entire day and/or when it was hard for me to separate the various observations from each other, a conservative approach was used. This meant that only the reported observation(s) that had both position and numbers observed, was registered, and not observations that was just mentioned to be in the same approximate area. Two observations that were reported between March 1st, 2019 and June 3rd, 2019 were not added in any part of the analysis conducted in this study.

2.2.3 Quality check of observations

At the end of the fishing season, when there was a smaller chance of people observing any more ABFT in 2018, some of the more doubtful or less credible observations collected needed to be quality checked. This was to check whether the different observations actually were of ABFT, or whether some other species that can easily be confused with ABFT, had been observed, such as porpoise (*Phocoena phocoena*), killer whales (*Orcinus orca*) or other kinds of marine mammals.

Factors used to accept an observation:

- If the observer provided scientific documentation such as pictures and videos either of the ABFT or from sonars and other acoustic equipment that had recorded ABFT.

- If no pictures or videos of the observation existed, a look on the credibility of the observer was done. Fisherman and other experienced seamen were deemed more credible than persons not used to spend time at sea.

- The location of where the observation was made also played a role in substantiating the observation, as some areas were more and less likely to have ABFT present than others. However, if an observation was made in an area where it was less likely for ABFT to be, this was not a good enough reason to discard that particular observation.

- The more people that saw the particular observation, the more credible it was deemed.

2.3 Data presentations and statistical analysis

After the various observational data was collected, they were systemized in Microsoft Office Excel along with information that was provided with several of the observations. Maps of the Norwegian coast with bubble plots of ABFT observations made inside the Norwegian EEZ for 2016, 2017 and 2018, were made using the ggmap-package in R-statistical program (Kahle and Wickham, 2013). This allowed for a visual overview of the distribution of ABFT in Norwegian waters over the past three years.

All statistical analyses were conducted in R-statistical software (R Development Core Team, 2013), where $p < 0.05$ was chosen as significant level with a 95% confidence interval for all tests. An analysis of the overall change in ABFT distribution and migration pattern within Norwegian waters in space and time, was conducted.

Weight, length and age

A one-way ANOVA was performed for individual ABFT weight, SFL, condition and age per year. If the one-way ANOVA gave a significant p-value ($p < 0.05$) between the years, a post hoc Tukey HSD-test was performed to determine which years differed significantly from each other. Linear regression analysis of weight and length data was made. A 2nd and 3rd order polynomial allowed to test for eventual curvature in the data. The model selection criterium used was Residual Sum of Squares (RSS), to determine which model had lowest unexplained variability. A reduction in RSS needed to be significant to be accepted as an improvement in the model selection procedure, i.e. I followed the principle of parsimony.

Observations

A Chi-square goodness of fit test was performed to test for differences in how many observations that were made each year from 2012 to 2018 to the expected probability, assuming an even distribution of observations over the years.

Size of school to time of year

A binomial logistic regression analysis was performed for the past three years (2016 to 2018) on observed school sizes, having two categories ("small" and "large"), with Julian days as a continuous predictor variable. School sizes of 1-10 individuals were categorized as "small" and everything above 10, as "large". The time span in days used included July as the starting point and December as the end.

Length dependent migration hypothesis

A two-sample t-test was performed to check for differences in SFL above and below 62°N over the past three years (2016 to 2018). Above 62°N was considered "high" latitude and below 62°N was considered "low", in the analysis. The latitudinal position of 62°N was chosen based on the likely historic immigration routes of ABFT to Norwegian coastal waters during the 1950's to mid-1980's (Figure 4).

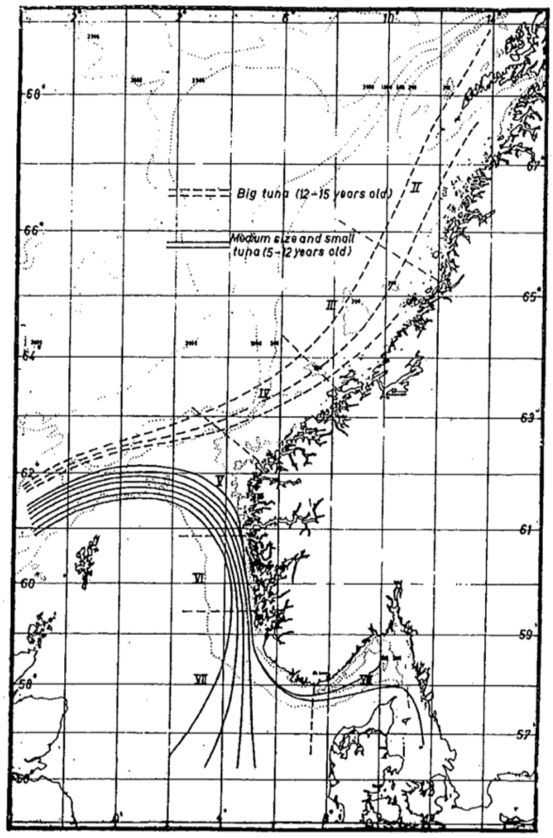

Figure 4: *Likely historic immigration routes of ABFT to Norwegian coastal waters during 1950-60's, with latitude on the Y-axis and longitude on the X-axis. Numerals II-VIII refer to historic fishing grounds. Solid lines are the medium and small-sized (5-12 years) ABFTs migration pattern and dotted line is big (12-15 years) ABFT migration pattern. Retrieved from Hamre (1961).*

3. Results

3.1 Capture data from the fishery

ABFT quotas increased annually from the trial-fishery started in 2014. During the targeted commercial fishery (2016 to 2018), the quotas was almost entirely fished except for in 2018 (Table 2).

Table 2: *Annual Norwegian ABFT total quotas (including quotas set aside to bycatch), targeted catches and bycatches from 2014 to 2018.*

	Total Quota (tons)	**Targeted catch (tons)**	**Bycatch (tons)**
2014	30.97	0	0
2015	36.57	0	8.70
2016	43.71	39.64	4.15
2017	52.48	47.75	10.48
2018	104.0	10.13	1.65

The overall range in catches was 120-465 kg in weight, 184-297 cm in SFL and 6 to 14 years old individuals, from 2016 to 2018 (Table 3). There were several bycatches of ABFT from 2016 to 2018 (Table 6). Most bycatches of ABFT were made by different kinds of fishing trawls and by commercial fishing vessels targeting mackerel, Atlantic horse mackerel, herring, blue whiting and shrimp (*Pandalus borealis*).

Table 3: *Minimum, mean and maximum weights, SFLs and ages of ABFTs caught in Norwegian waters from 2016 to 2018.*

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

3.1.1 Biological measurements 2016 to 2018

The mean weight of ABFT was highest in 2016 and lowest in 2018, but no significant differences in individual ABFT weights between the years were found ($p = 0.23$). The extreme values for weight were highest (465 kg) in 2018 (Figure 5).

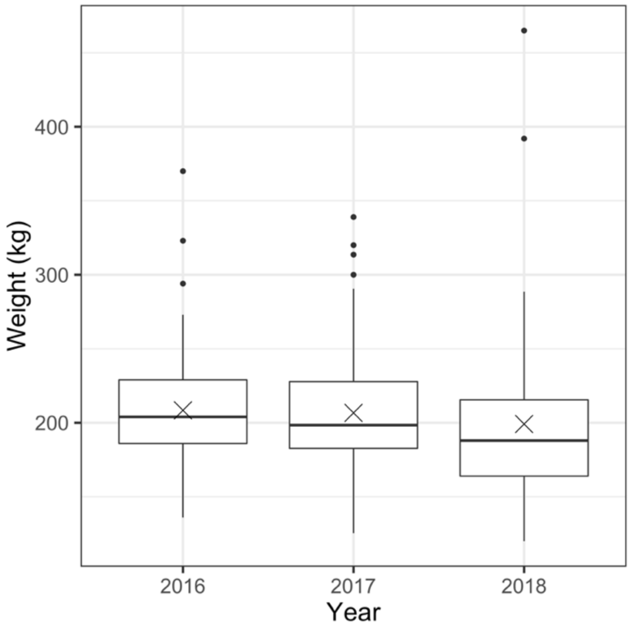

Figure 5: *Boxplot showing the weight of 510 ABFTs caught inside the Norwegian EEZ from 2016 (n = 201), 2017 (n = 248) and 2018 (n = 61). The thick black line inside each box is the median, the x inside each box is the mean value for weight, each given year. The upper and lower borders of the boxes represent the upper and lower quartiles. The points above each box are the extreme values of weight for each year.*

The mean SFL was highest in 2017 and lowest in 2018. A significant difference in SFL between 2017 and 2016 ($p < 0.01$) and 2018 and 2017 ($p < 0.01$), was found. The most extreme values for SFL were found in 2018 (Figure 6).

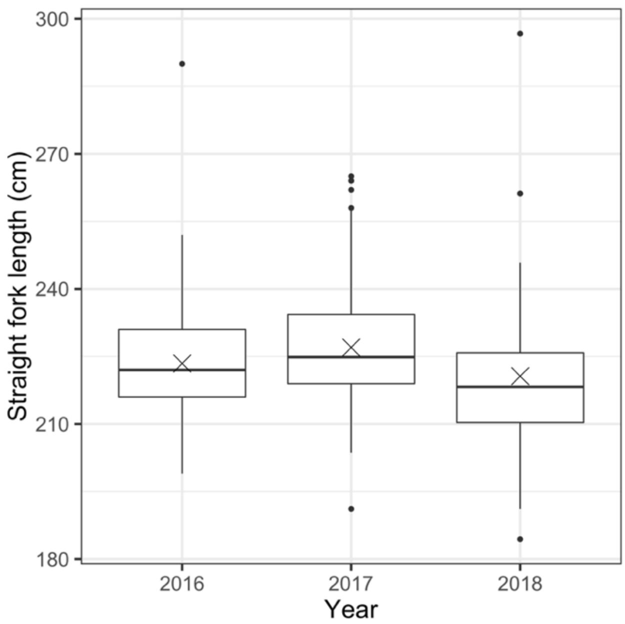

Figure 6: *Boxplot showing SFL of 509 ABFTs caught inside the Norwegian EEZ each year from 2016 (n = 201), 2017 (n = 248) and 2018 (n = 60). The thick black line inside each box is the median, the x inside each box is the mean value for straight fork length, each given year. The upper and lower borders of the boxes represent the upper and lower quartiles. The points above each box is the extreme values of length for each year.*

The distribution in SFL of the ABFTs caught in Norwegian waters from 2016 to 2018 was close to normally distributed with most being around 220 cm in SFL (Figure 7).

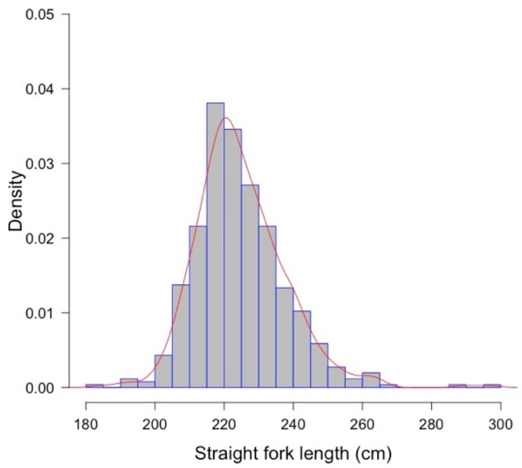

Figure 7: *Density histogram of SFL of 509 ABFTs caught in Norway from 2016 to 2018. The red line is the density curve which represents the mean values.*

3.1.2 Length-dependent migration hypothesis

A significant difference in SFL between ABFT north and south of 62°N, was found ($p < 0.05$). ABFT caught south of 62°N were on average 5 cm longer than ABFT caught north of 62°N, where ABFT south of 62°N had a mean SFL of 228 cm and ABFT north of 62°N had a mean SFL of 223 cm.

3.1.3 Length/weight relationship and condition

The linear regression of the log transformed Equation B gave $\beta = 2.49$. The best model was the model with the 2nd order polynomial for SFL (1st vs 2nd order polynomial model: $F_{3,499} = 4.5734$, $p < 0.01$, the 3rd order did not lead to any improvement $p = 0.71$) and an interaction between this predictor and year ($F_{4,99} = 3.1407$, $p < 0.02$) (Figure 8).

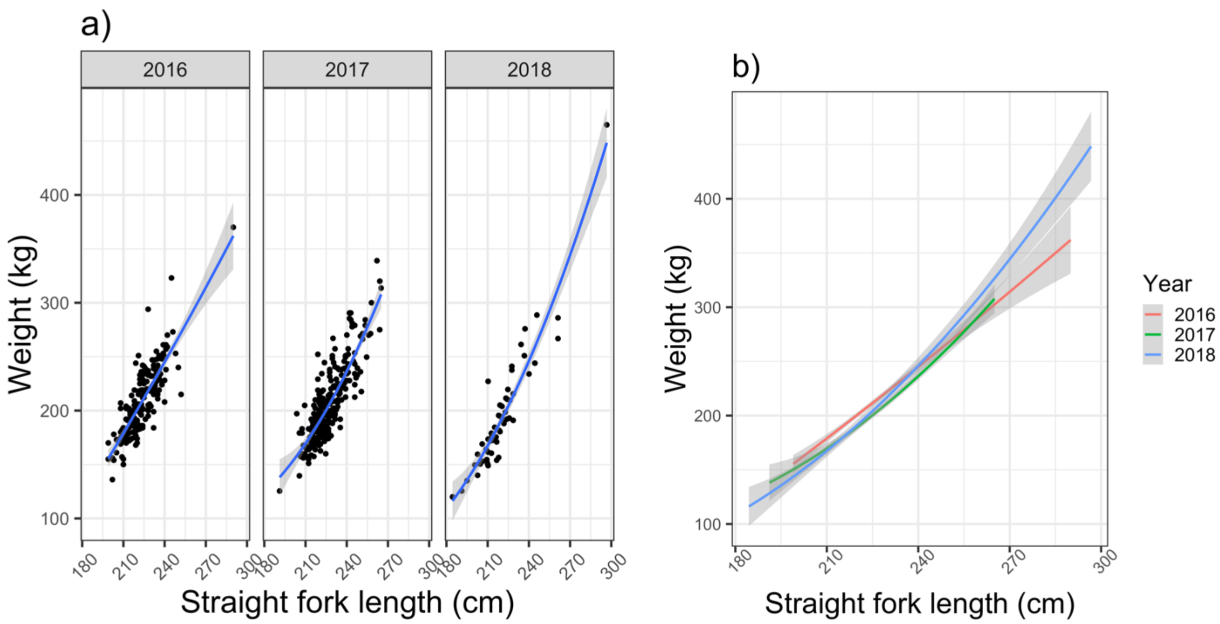

Figure 8: *a) Three scatter plots showing the length/weight relationship of a total of 508 ABFTs caught inside the Norwegian EEZ from 2016 (n = 201), 2017 (n = 248) and 2018 (n = 59). The blue line is a fitted non-linear 2rd degree polynomial regression line, with the blurred grey area being the 95% confidence interval of the fitted values. b) The predicted length/weight relationship plotted together for each year.*

A significant difference in condition (K) of ABFT between 2017 and 2016 ($p < 0.01$) and 2018 and 2016 ($p < 0.05$), was found. Condition (K) was highest in 2016 and lowest in 2017 (Figure 9). K-values ranged from 1.34 to 2.48, with mean K = 1.80 and SD = 0.1.

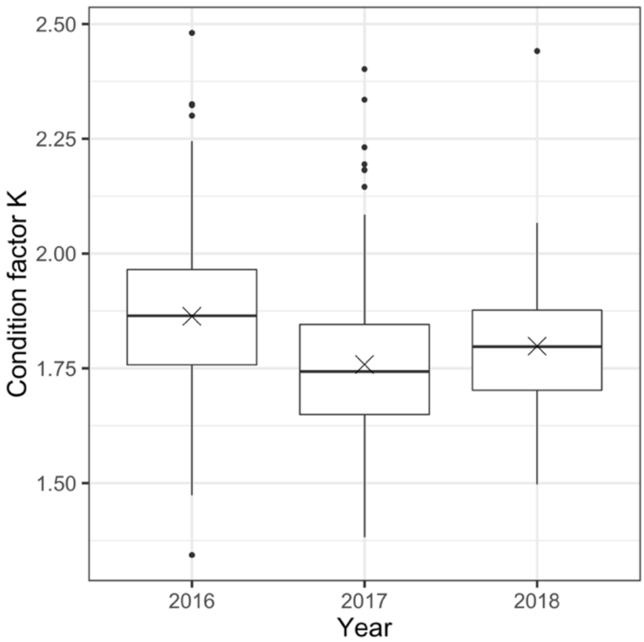

Figure 9: *Boxplot showing estimated condition of 508 ABFTs caught inside the Norwegian EEZ from 2016 (n = 201), 2017 (n = 248) and 2018 (n = 59). The thick black line inside each box is the median, the x inside each box is the mean value for condition, each given year. The upper and lower borders of the boxes represent the upper and lower quartiles. The points above each box are the extreme values of condition for each year.*

3.1.4 Age

The age-determined along with the age-estimated individuals from 2016 and 2017 ranged from 191 to 265 cm in SFL and consisted of 449 individuals (n = 201 and n = 248 for 2016 and 2017, respectively) ranging from 6 to 14 years of age (Table 4 and Figure 11). The age-estimated individuals of ABFT from 2018 ranged from 184 to 297 cm in SFL and consisted of 59 individuals (Table 4).

Table 4: *Total count of ABFTs per age (6 to 14 years) per year from 2016 to 2018, showing age-determined individuals along with age-estimated individuals from this study, added together.*

	Age									
Year	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Total**
2016	0	1	18	52	64	45	15	5	1	201
2017	1	5	32	66	82	36	20	5	1	248
2018	2	1	9	21	13	6	5	2	0	59
Total	**3**	**7**	**59**	**139**	**159**	**87**	**40**	**12**	**2**	**508**

3.1.4.1 Age distribution of ABFT in 2016 to 2018

The highest frequencies of ages at SFL in 2016 occurred around 220 cm (Figure 10). The mean age was 10.0 years (Table 4). The highest frequencies of ages at SFL in 2017 occurred around 220 cm (Figure 10). The mean age was 9.8 years. The highest frequencies of ages at SFL in 2018 occurred around 220 cm (Figure 10). The mean age was 9.5 years.

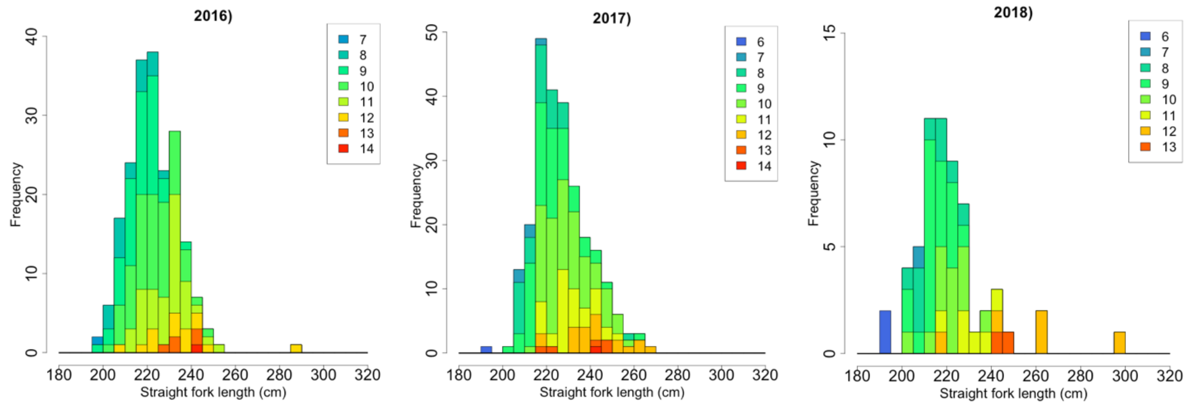

Figure 10: 2016) *Frequency of age at SFL for 201 ABFTs from 2016, including all age-determined (n = 190) and all age-estimated ABFTs (n = 11). Each colour represents age in years, ranging from 7 to 14 years of age.* 2017) *Frequency of age at SFL for 248 ABFT from 2017 including all age-determined (n = 226) and all age-estimatd ABFT (n = 22). Each colour represents age in years, ranging from 6 to 13 years of age.* 2018) *Frequency of age at SFL of 59 age-estimated ABFT from 2018. Each colour represents age in years, ranging from 6 to 13 years of age.*

A significant difference in age was found between 2016 and 2018 ($p < 0.05$), where the mean age in 2018 was 0.5 years younger than the mean age in 2016 (Figure 11). The mean age was highest in 2016 and lowest in 2018. The extreme values for age were highest in 2017 (Figure 11).

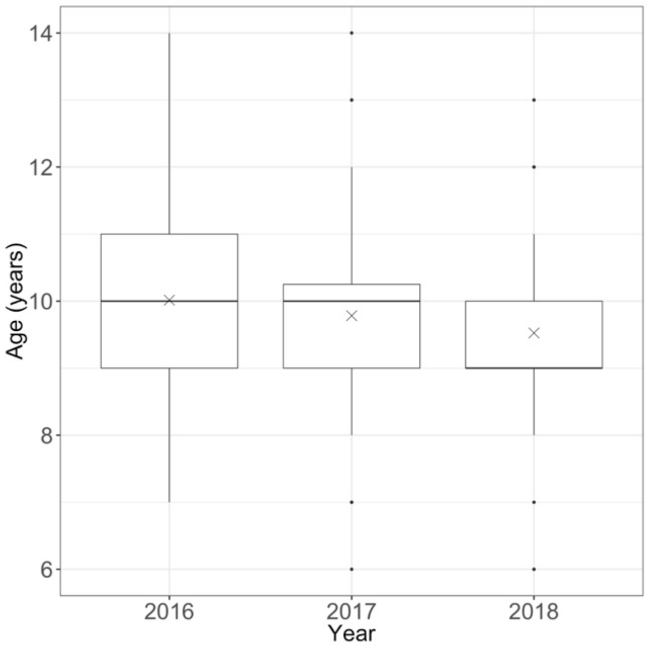

Figure 11: *Boxplot showing ages of 508 ABFTs caught inside the Norwegian EEZ each year from 2016 (n = 201), 2017 (n = 248) and 2018 (n = 59). The thick black line inside each box is the median, the x inside each box is the mean value for age, each given year. The upper and lower borders of the boxes represent the upper and lower quartiles with the points above the boxes being the extreme values of age for each year.*

3.2 Observational data

3.2.1 Count of already existing observations and observations collected during this study

Altogether 63 observations of ABFT in Norwegian waters were registered prior to this study; 30 observations from 2017, 16 observations from 2016, 10 observations from 2015, 4 observations from 2014 and 3 observations from 2013 (including catches and bycatches from the fishing fleet). From the already registered observations, 43 observations were made by fishing vessels and the rest (n = 20) from recreational fishermen and research vessels. A total of 151 observations were reported in this study, where 150 were approved, as one of the observations was highly likely to be of orcas in Fensfjorden. Thus, a total of 213 observations of ABFT were registered from inside the Norwegian EEZ between 2012 and 2018. The number of observations registered for each year, ranged from one in 2012 to 105 in 2018 (Figure 12). Most observations of ABFT occurred between 2016 to 2018 (Figure 12). Observations collected in this study (n = 150) came from several sources: 37 observations from the online registration form, 20 from fishing attempts on ABFT by the licensed fishing vessels, 11 from bycatches, 16 from the satellite tagging project and the rest (n = 66) came from Facebook, internet searches, and mail and phone calls from the public. Two observations were received between March 1st and June 3rd, 2018, one from June 2017 and one from July 2018. These were not included in any of the analyzes in this study.

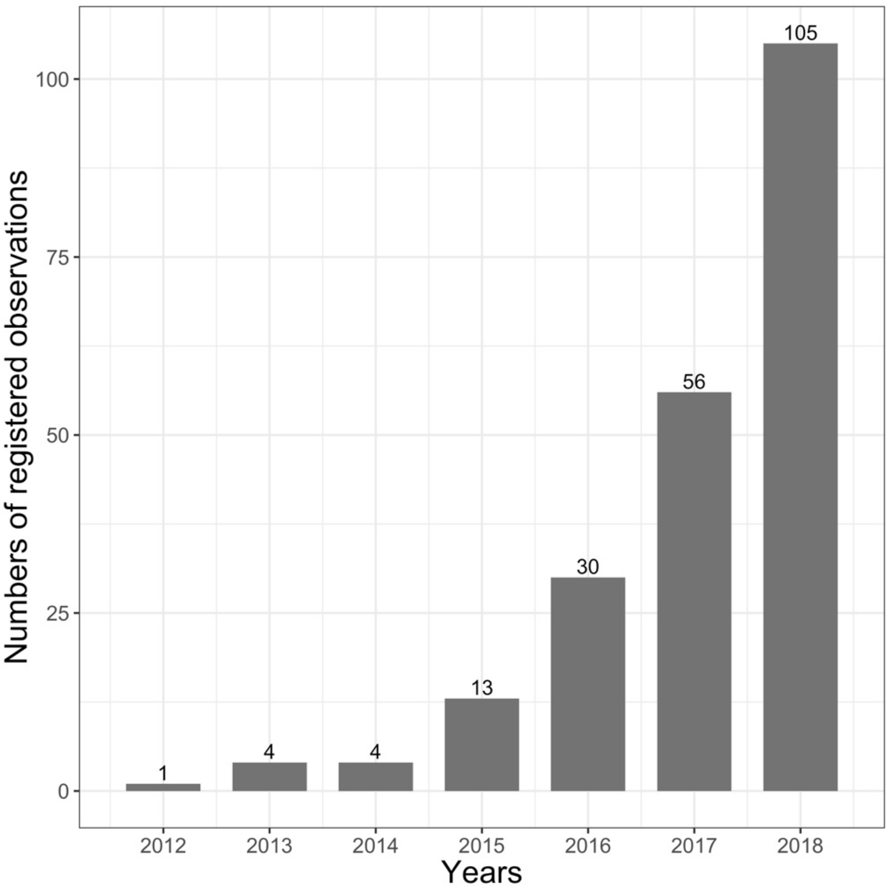

Figure 12: *Barplot showing count (number above each bar) of a total of 213 registered observations from inside the Norwegian EEZ over the years from 2012 to 2018. Observations include commercial catches, bycatches, strandings, echo and sonar recordings and visual observations, where one catch (being either commercial or bycatch) equals one observation.*

A significant increase in observations of ABFT were found in Norwegian waters from 2012 to 2018 (Chi-square value = 288.6, df = 6, $p < 0.01$).

Weather conditions

From altogether 213 observations, only 45 (n = 3 from 2016, n = 12 from 2017 and n = 30 from 2018) contained information about weather conditions. 44 of these were made on days with good weather conditions. One observation were made in bad weather conditions with winds up to 12.3 m/s and waves up to 4 meters.

Behaviour

Two observations had information about ABFT swimming calmly at the surface. A remaining 140 observations from 2012 to 2018 were made of ABFT exhibiting hunting and feeding behavior at or near the surface. This behavior was seen by a lot of activity such as jumping, splashing and rapid swimming movements (Figure 13 and Appendix G) and also with seabirds hunting in the same area. In some cases, observers saw escaping prey. These observations were most often involving juvenile mackerel, but also included sprat, herring and garfish (*Belone belone*). A total of 71 observations had no information about behavior.

Figure 13: *Two ABFTs hunting at the surface during 2015, where the ABFT on the left is almost jumping entirely out of the water. Photo: Enrico Wyrwa.*

3.2.2 Observations of ABFT 2016 to 2018

The majority of registered observations of ABFT came from 2016 to 2018 (Figure 12) and most observations were made between August and October each year (Table 5). The latitudinal positions of observations of ABFT made between 2016 and 2018 ranged from 57°44N to 76°20N with a mean latitude of observations at 61°36N. The vast majority of observations of ABFT between 2016 to 2018 were made between 58°N and 65°N, and relatively near the Norwegian coastline for all years where observations were being made (Figure 14, 15 and 16).

Table 5: *Count of registered observations of ABFT 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**

2016

Observations were made from August to November, with most observations registered in September (n = 9) and October (n = 12) (Table 5). The number of ABFTs observed in one limited area during 2016 ranged from 1-6 up to approximately 1000 individuals (Figure 14). The latitude of observations in 2016 ranged from 57.8°N to 64.5°N (Figure 14). A total number of 29 out of 30 observations were plotted in Figure 14, as one observation was lacking position.

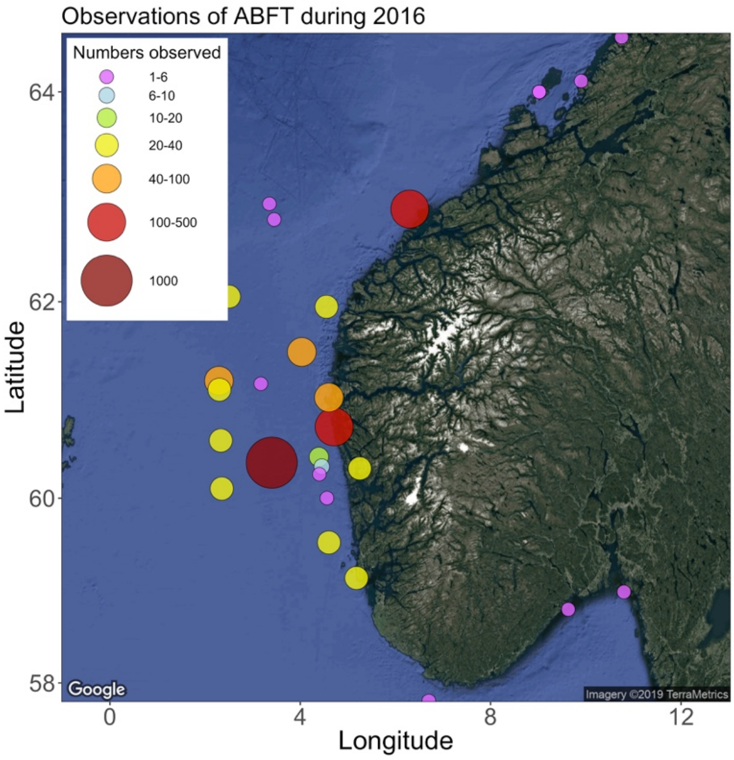

Figure 14: *Map of the south-western part of the Norwegian coast, with bubble plot of 29 observations of ABFT observed in Norwegian waters during 2016. Colors and sizes of bubbles represent the approximate numbers per observation. Observations include commercial catches, bycatches, ABFT caught in fish farms, sonar and echo recordings and visual observations in 2016.*

2017

Observations were made from February to October, with most observations registered in August (n = 30) and September (n = 22) (Table 5). Numbers of ABFT observed in one area during 2017 ranged from 1-6 to approximately 6000 individuals which were seen over a distance of 10 nautical miles (Figure 15). Latitude of observations in 2017 ranged from 57.4°N to 68.9°N (Figure 15). A total of 53 out of 56 observations were plotted in Figure 15, as three observations were lacking positions.

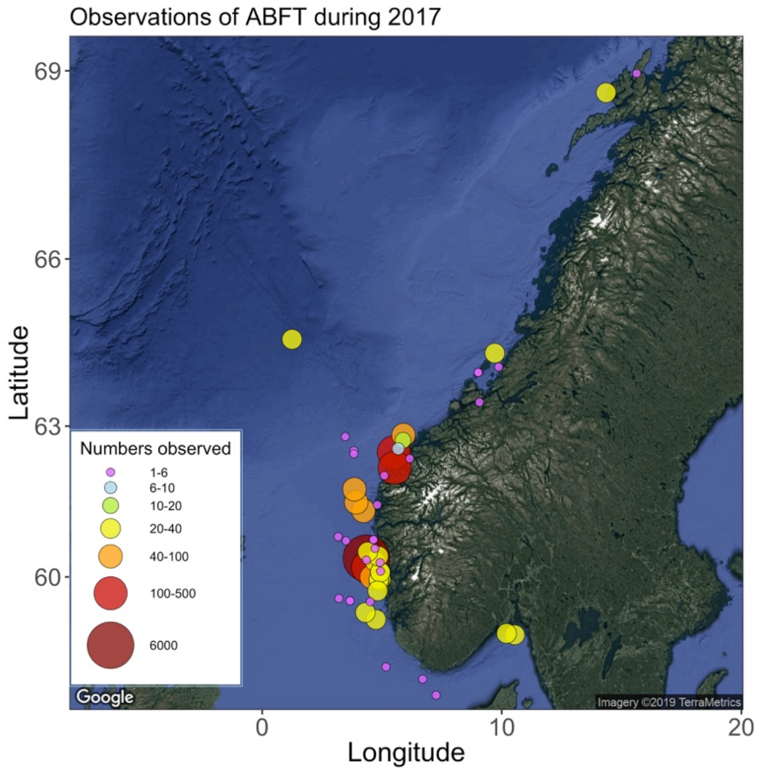

Figure 15: *Map of the Norwegian coast, with bubble plot of 53 observations of ABFT observed in Norwegian waters during 2017. Colours and sizes of bubbles represent the approximate numbers per observation. Observations include commercial catches, bycatches, ABFT caught in fish farms, sonar and echo recordings and visual observations in 2017.*

2018

Observations were made from July to December, with most observations registered in August (n = 36) and September (n = 45) (Table 5). Numbers of ABFT observed in one limited area during 2018 ranged from 1-6 to approximately 1000 individuals (Figure 16). Latitude of observations in 2018 ranged from 57.4°N to 76.2°N (Figure 16). A total number of 100 out of 105 observations were plotted in Figure 16, as five observations were lacking positions.

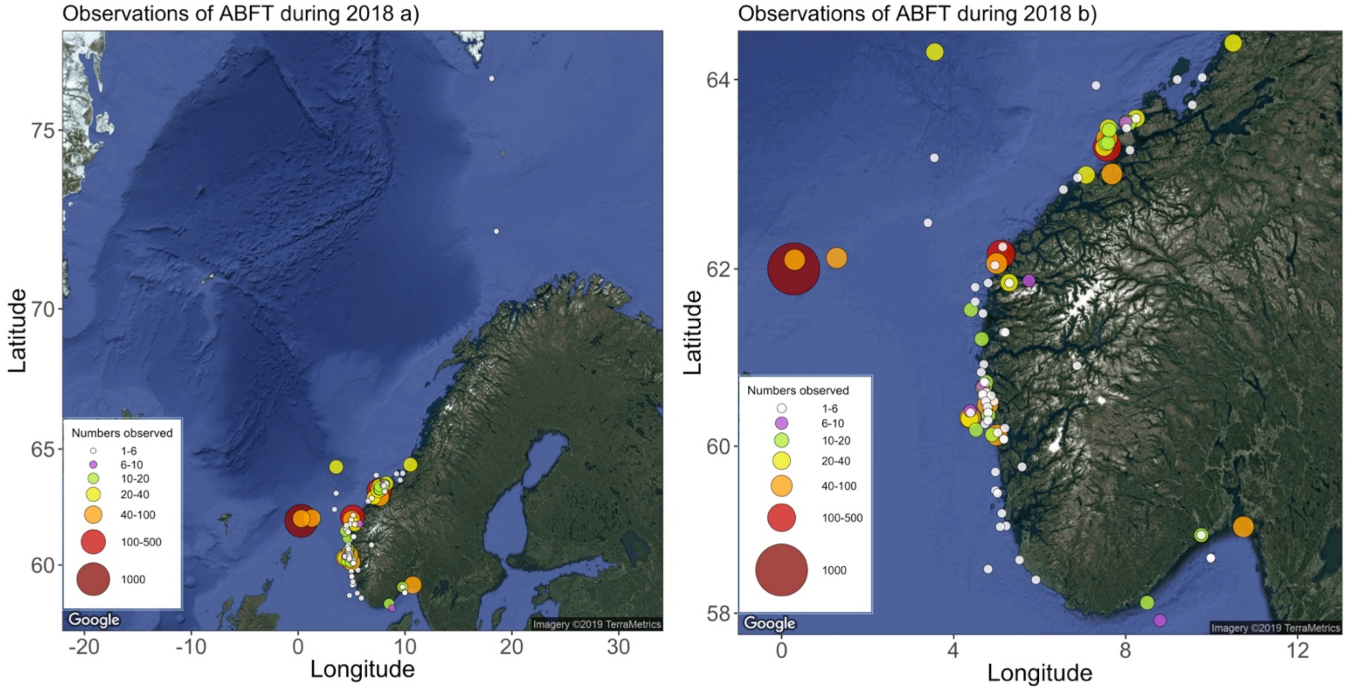

Figure 16: *Observations of ABFT during 2018 a) Map of the entire Norwegian coast along and up to Svalbard, with bubble plot of 100 observations of ABFT observed in Norwegian waters during 2018. Observations of ABFT during 2018 b) A map of the south-western part of the Norwegian coast, with bubble plot of nearly all (n = 98) observations of ABFT observed in Norwegian waters during 2018. Colours and sizes of bubbles represent the approximate numbers per observation. Observations include commercial catches, bycatches, ABFT caught in fish farms, strandings, sonar and echo recordings and visual observations in 2018.*

3.2.3 Size of school to time of year

In 2016, sizes of schools observed ranged from 1-6 up to very large schools of approximately 1000 individuals. Most observations were of small schools consisting of 1-6 individuals (n = 13) mostly found in August. The largest school of approximately 1000 individuals was observed in October (Figure 17). In 2017, observed school-size ranged from 1-6 up to large schools of approximately 100-500 individuals. Most observations were of small schools (n = 29) consisting of approximately 1-6 individuals mostly found in August. The largest schools of approximately 100-500 (n = 4) individuals were observed in August and September (Figure 17). In 2018, observed school-size ranged from 1-6 up to a very large school of approximately 1000 individuals. Most observations were of small schools consisting of approximately 1-6 individuals (n = 62) mostly found in September. The largest school of approximately 1000 individuals was observed in October (Figure 17).

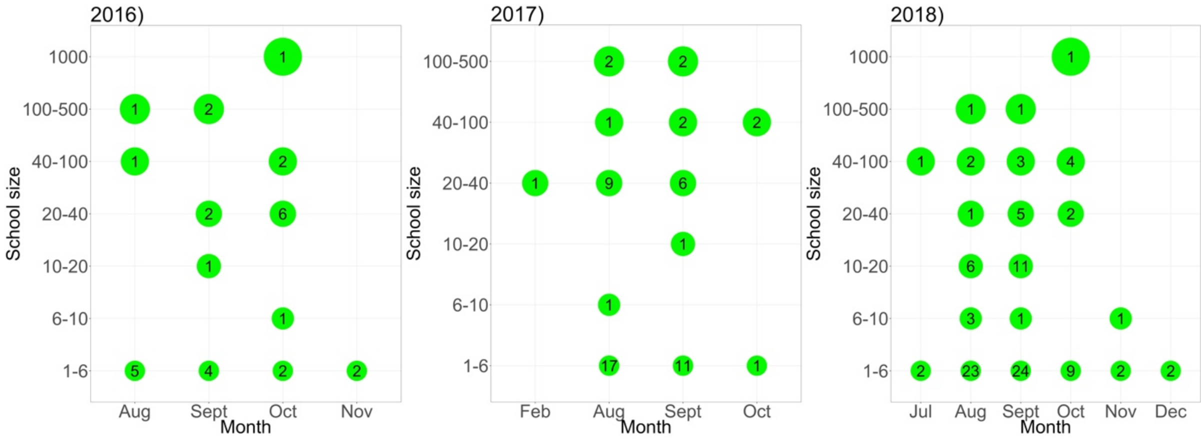

Figure 17: *2016) Showing a total of 30 observations with count of observations (number inside each bubble) of different school sizes of ABFT during different months in 2016. 2017) Showing a total of 56 observations with count of observations (number inside each bubble) of different school sizes of ABFT during different months in 2017. 2018) Showing a total of 105 observations with count of observations (number inside each bubble) of different school sizes of ABFT during different months in 2018.*

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 year, defined by a significant negative 2nd order polynomial ($z = 2.44$, $p < 0.02$). The probability of encountering schools > 10 individuals was highest between mid-September to mid-October (Figure 18).

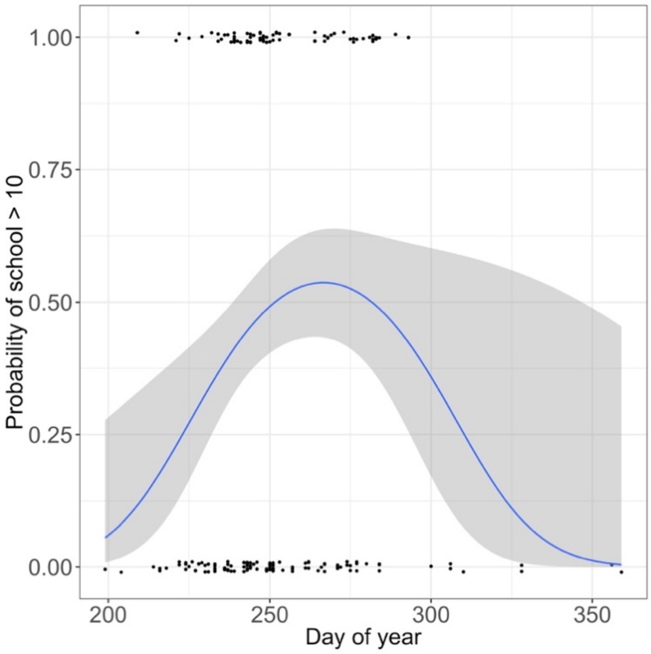

Figure 18: *Probability of encountering large school sizes (> 10 fish) of ABFT by days during the year, where day 200 – 350 represent the start (July) and the end (December) of the ABFTs feeding season in Norwegian waters. The blue line represents the best model that includes a significant 2nd order polynomial. The shaded area represents the 95% confidence interval for the model line.*

3.2.4 Types of observations registered from 2016 to 2018

Visual observations of ABFT jumping and/or hunting at the surface, made up the majority of registered observations from 2016 to 2018 (Table 6). Other types of observations that were registered came from commercial catches, bycatches, acoustic recordings (sonar and echo-sounder) and strandings (Appendix D, E and F). All of these types of observations were normally made together with visual confirmation of sightings of ABFT hunting at the surface.

Table 6: *Summary of 191 observations with the count of the different types of observations that were made from 2016 to 2018, where "Acoustic recording" = recording by either sonar, asdic or echo sounder, "Visual and Acoustic recording" = both sighting of ABFT in the surface and recording by either sonar, asdic or echo sounder, "Bycatch" = All bycatches, "Commercial catch" = every catch of ABFT through the Norwegian directed fishery, "Stranding" = ABFT found dead on the shoreline, "Visual" = sightings of ABFT at the surface and "Fish farms" = every ABFT getting trapped inside fish farms.*

Type of Observation	**Acoustic recording**	**Visual and Acoustic recording**	**Bycatch**	**Commercial catch**	**Stranding**	**Visual**	**Fish farms**
Count:	9	13	11	13	3	136	6

Figure 19 is showing schools of what was likely to be of ABFT recorded on sonar. Fishermen aboard M/S "Bluefin" estimated that each red dot on the sonar corresponded to a minimum of 200 ABFT (Figure 19).

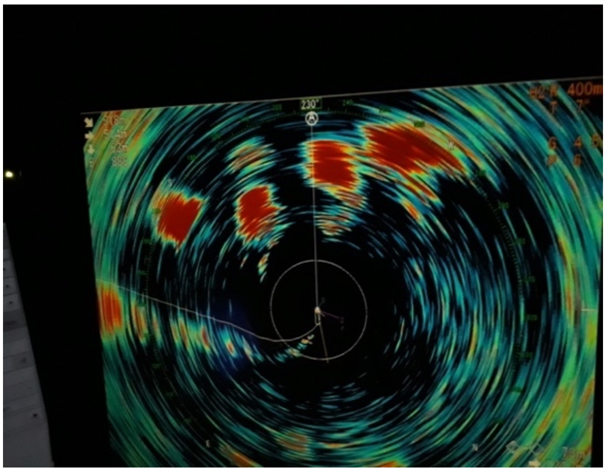

Figure 19: *Sonar picture retrieved from the fishing season in 2017, of four schools of ABFTs, where it was estimated by fishermen aboard M/S "Bluefin" to be a total of 800-1400 large (+250kg) ABFT. Observations like this were normally made together with visual confirmation of ABFTs hunting juvenile mackerel at the surface in the same area. Photo: M/S "Bluefin" / Atle Nekkøy.*

3.2.5 ABFTs trapped inside fish farms from 2016 to 2018

A total of six registrations of ABFT getting trapped inside fish farm pens were made between 2016 and 2018 (Figure 20). The ABFT managed to get trapped inside the pens by penetrating themselves through the walls of the fish pens.

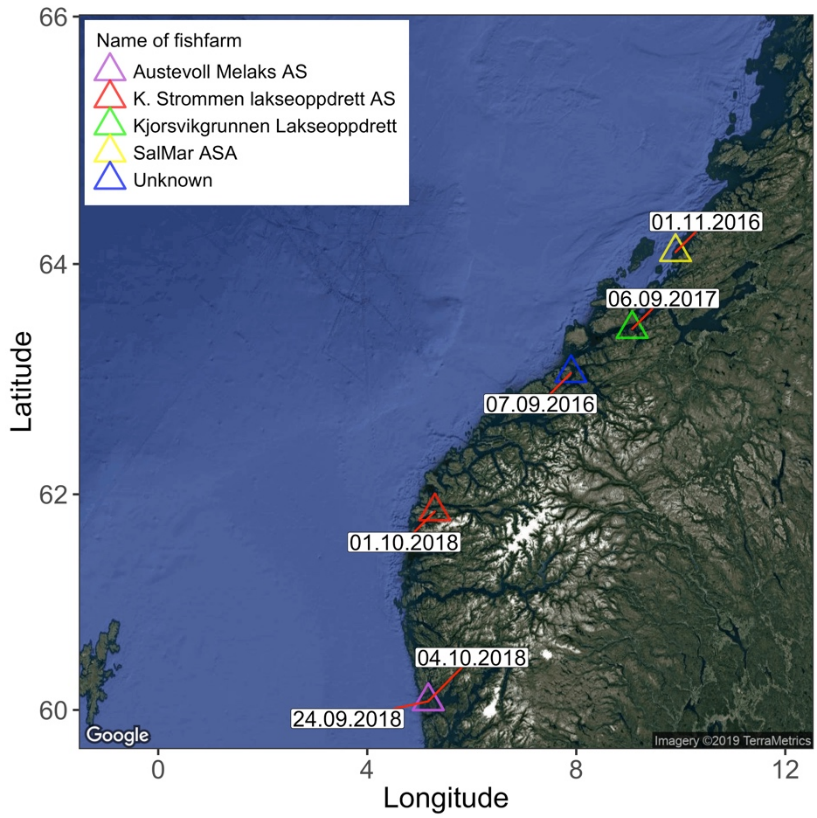

Figure 20: *Map of the south-west coast of Norway with positions and date when the ABFT was captured and taken out of each fish farm. A total of three ABFT got trapped in 2018; One in a fish farm owned by K. Strømmen lakseoppdett AS and two in a fish farm owned by Austevoll Melaks AS. One ABFT got trapped in 2017 in a fish farm owned by Kjørsvikgrunnen Lakseoppdrett. Two ABFTs got trapped in 2016; one in a fish farm owned by Salmar ASA and one in an unknown fish farm.*

3.2.6 Strandings of ABFT during 2018

Observations of stranded ABFTs were made at three different locations during 2018, with one in Fjaler, Hellevik on the 22nd of December, one at Husøya, Ona on the 27th of October and one in Nærøyfjorden on the 25th of December (Figure 21). These were all sightings of large dead ABFT that were either washed ashore or floating in shallow water very close to land (Appendix F). The ABFTs stranded in Fjaler, Hellevik and in Nærøyfjorden both had visible skin damage on their bodies, snout and head regions (Appendix F, Figure III: B), C) and D). The ABFT stranded in Nærøyfjorden was at least 186 cm in SFL. The cause of death in all three cases were unknown. There were no reported registrations of stranded ABFT from 2016 and 2017.

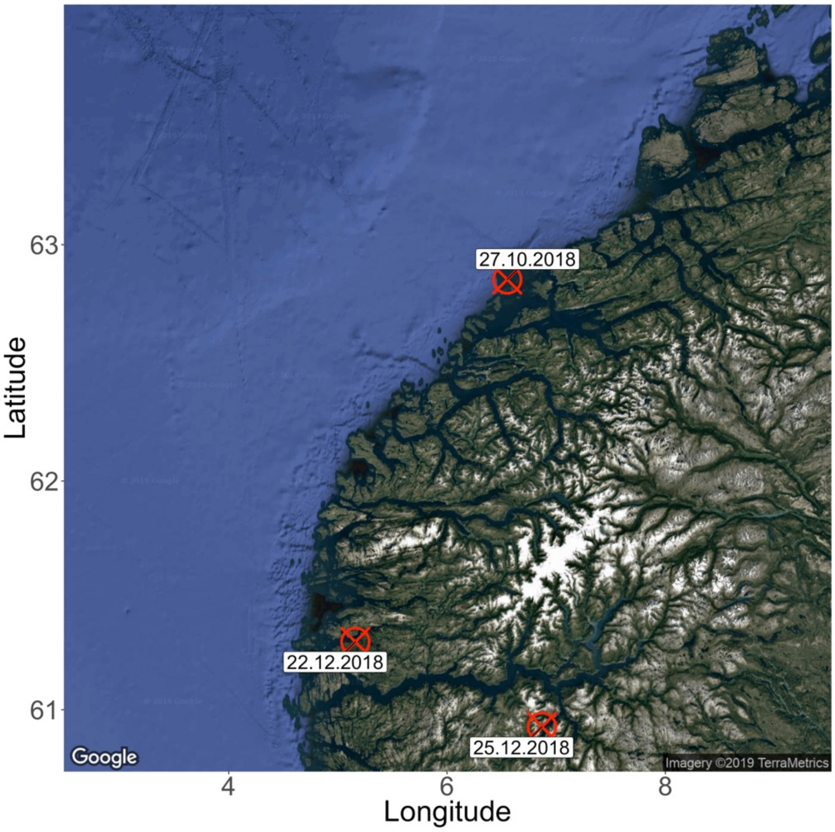

Figure 21: *Map of the south-western coast of Norway with red markers showing positions with date of observation of stranded ABFT in 2018. One ABFT had stranded on Husøya at Ona, one in Hellevik in Fjaler and one in Nærøyfjorden in Aurland, from north to south, respectively.*

4. Discussion

The ABFT has reestablished its historical migration pattern into Norwegian waters in recent years, after being absent from Norwegian waters for several decades (Nøttestad et al., 2017b). The main goal of this study was to determine the basic biology and get insight into the spatio-temporal distribution and ecology of ABFT along the Norwegian coast, during recent years. In this study, I present various results on weights, lengths and ages of individual ABFT captured by the Norwegian commercial fishery and of bycatches from 2016 to 2018. Moreover, the geographical distribution, behavior and ecology of ABFT in Norwegian waters, are also presented, based on observations and information collected from the public during the course of this study.

My results show that mainly larger (overall range in catches: 120-465 kg in weight and 184-297 cm in straight fork length (SFL)) and mature (6 to 14 years) ABFT in good condition ($K > 1.5$), have been visiting the Norwegian coast in recent years. A significant increase in number of observations of ABFT were made in Norwegian waters from 2012 to 2018, coinciding with increased stock size during the same period (ICCAT, 2018). Most observations were made in August and October from 2016 to 2018, where most observations were found along the Norwegian coast, relatively close to shore. The latitudinal distribution of observations expanded for each year between 2016 and 2018, indicating that increased numbers of ABFT need more space, and/or that they follow their prey and therefore expand further north along the coast of Norway. The numbers of ABFT observed in a limited area ranged from solitary individuals up to large schools of approximately 1000 individuals, showing a highly dynamic schooling behavior. There were significantly higher chances of observing larger schools (> 10 individuals) between mid-September to mid-October than earlier and later in the year. As many as 6000 individuals divided into several schools over a distance of 10 nautical miles, were also observed. Most observations were visual observations of ABFT exhibiting hunting and feeding behavior at the surface, but other types of observations such as acoustic recordings (echosounder and sonar), commercial catches, bycatches, ABFT caught in fish farms and strandings of dead ABFT, were also collected.

4.1 Discussion of materials and methods and uncertainty of results

As there were lack of standardization in methods used for treatment of fish prior to weighing and different methods for measuring length, a lot of effort was put into figuring out the different procedures for handling of fish prior to weighing, between the certified fishing vessels, as well as converting and estimating the biological data, in order to standardize them for further statistical analysis. A lot of time and effort also went into reaching out to the public through the different social media and communication platforms, and moreover, into systemizing and analyzing the plethora of observations that were retrieved in this study. Since the catch-data were only based on relatively few catches and bycatches from the last three years, we cannot exclude that smaller and younger or even larger and older individuals than the ones found in this study, have not been present in Norwegian waters during recent years.

Equation A (SFL = 0.9596*CFL + 2.0985) was used when converting CFL to SFL, in this study. This is an updated conversion factor suggested by Lombardo et al. (2017) from the one previously adopted by ICCAT-SCRS: SFL = 0.955*CFL (Parrack and Phares, 1979). Lombardo et al. (2017) argue that the SFL-CFL relationship currently adopted by ICCAT-SCRS underestimates the real length of the fish and was therefore not used in this study. The SFLs estimated in this study, is therefore likely to be more accurate than the ones previously estimated with SFL = 0.955*CFL.

Fulton's condition factor (K) was used to calculate the condition of ABFT in Norwegian waters from 2016 to 2018. However, Fulton's condition factor assumes isometric fish with a growth constant of $\beta = 3$. The linear regressions analysis of length/weight relationship conducted in this study, did however, show a growth constant of $\beta = 2.49$. This means that the ABFT analyzed in this study, had a negative allometric growth, meaning that they get slightly leaner as they increase in size. This is consistent with another study done on the length/weight relationship of ABFT captured in the Mediterranean Sea (Santamaria et al., 2009). Therefore, the use of Fulton's condition factor was not a very accurate method in determining the condition (K) of ABFT in Norwegian waters in recent years but can still serve as a method for determining general condition (K) and if feeding condition has been good or bad.

There are several methods for estimating ages of bluefin tuna (Hamre, 1962; Prince et al., 1985; Jenkins and Davis, 1990), but the current method used in ICCAT is by analyzing samples of the first dorsal spine. In this study, the large part of the age data was retrieved from already sampled ABFTs, based on first dorsal spines (Arrizabalaga et al., 2019), whereas some were age-estimated based on an age-length key made from the already age-determined individuals from 2016 and 2017. Estimating age compositions based on age-length keys have been widely used by fisheries biologists since 1934 but brings with it some possible biases and uncertainties (Kimura, 1977). There are, however, also some uncertainties of accuracy in age-determination of individual fish based on interpreting growth rings on skeletal hard parts, and especially of tuna older than 6 to10 years as rings/growth bands often are hard to interpret in larger adults (Hurley and Iles, 1983; Lee et al., 1983). The certainty of the age-determined individuals is, however, higher than the age-estimated individuals but the age-estimation in this study, should still give a fair idea of the real ages.

There are several biases and uncertainties regarding the use of observational data to estimate abundance and ecology of ABFT in Norwegian waters. In the following section I have mentioned what I have found to be the most important to highlight.

Observations are commonly used in science to estimate whale abundances (Sigurjónsson et al., 1989; Calambokidis and Barlow, 2004; Víkingsson et al., 2009). However, in contrast to this study, these are often systematic line transect surveys which apply a more even observational effort throughout the surveys. Despite operating with systematic line transects, Víkingsson et al. (2009) still had to adjust the observational effort to prevent bias due to possible systematic movements of whales. In this study, it has been no standardization of observational effort, which off course has been impossible to implement with the use of citizens from all along the coast. It was anticipated that a decrease of observations back in time from 2018 would occur due to much higher observational effort from the public during 2018, as a result of this study. This shows that even for dedicated observational surveys of whales, observational effort must be accounted for, and moreover, that the lack of standardization of observational effort in this study, is a huge bias that needs to be taken into consideration when estimating the abundance of ABFT. On the other hand, despite a much lower observational effort further out into the Norwegian Sea and higher effort closer to the coast, which could have led to an underestimation of distribution and biomass of ABFT further out into the Norwegian Sea, it could be that my results still show what is the actual migration pattern of ABFT near the coast, as this was the migratory trend also found in earlier periods (Hamre, 1957). The high density of observations made around 60.5°N, 4.5°E in 2018 close to the coastline (Figure 16), is probably largely due to the observational effort from the satellite-tagging project that year. These observations are likely to be an underestimation of how many ABFT that was actually in that area, as the researchers observed ABFTs almost continuously throughout several days and did not manage to register every single observation. However, there is a chance that observations of the same ABFTs was registered as separate observations and thus double registrations of the same ABFTs could have occurred. This needs to be taken into consideration, even though it is not very likely to have given the wrong perception of the actual abundance in the area. Other biases and uncertainties worth mentioning is that it was probably easier for people to remember more recent observations and assessments of the biological characteristics of ABFT observed was open to subjective interpretation. Also, observations may falsely have been classified as ABFT observations both visually and on acoustic equipment.

Several studies have used observations from citizens to map the migration pattern of animals, even with the possibility of biases arising when using observational data (Howard and Davis, 2009; Hurlbert and Liang, 2012; Supp et al., 2015). Despite these biases, citizen science can still be an important tool for ecological research, as it provides information that would otherwise be impossible to collect without the engagement of citizens (Dickinson et al., 2012). The observations of ABFT collected in this study, can therefore, provide important knowledge of the abundance, distribution and ecology of ABFT in Norwegian waters, recent years, and there is no doubt that the increase in observations is real and mainly because there is an increase in ABFTs visiting Norwegian waters every year.

Despite uncertainty of some observations, 150 out of 151 observations passed the quality check. However, many more observations could have been registered and investigated during this study. Sometimes, observers provided sufficient information about one or a few observations but mentioned that they observed more ABFT at several different sites during the same day. Examples of some observations that were not registered can be found in Appendix H. This additional information was difficult to quantify both in terms of numbers and sizes of ABFT observed. The position could also be difficult to determine with vague or missing information. For cases like this or similar to this, where only one or a few observations were registered, there could in fact have been information of several more observations made in the same approximate area during the same day. Since the main point of collecting observations was to provide a general overview of the magnitude and migration pattern of the return of ABFT to Norwegian waters, a conservative approach was adopted when registering observations.

4.2 Biological properties of ABFTs visiting Norwegian waters from 2016 to 2018

There was a clear trend that ABFTs visiting Norwegian waters were dominated by individuals larger than 120 kg and 184 cm from 2016 to 2018. No significant differences in weight were found between the years, but SFL was significantly longer in 2017 compared to 2016 and 2018. The sizes of ABFTs found in this study, equivalates to the same sizes of ABFT that were present in Norwegian waters from 1960 to 1965 (Nøttestad and Graham, 2004; Nøttestad et al., 2017a). Significantly higher condition (K) was found for ABFT in 2016 compared to 2017 and 2018. With SFL being significantly longer in 2017 compared to 2016 and 2018, and mean weight being lower in 2017 compared to 2016, although not significant, individuals in 2017 were leaner than individuals from 2016. Furthermore, with the mean condition (K) of ABFT being lowest in 2017, it is likely that they weighed less per length than individuals from 2016 and 2018. Seasonal variation in length/weight relationships have been documented for both juveniles and especially large ABFT, where 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 cost and feeding periods right after spawning (Chapman et al., 2011). Higher condition (K) in ABFT could also occur as a result of energy being saved due to skipped spawning (Jørgensen et al., 2006). The reasons for the differences in condition (K) of ABFT in Norwegian waters between 2016 and 2018, could therefore have been associated with relationships between how much energy went into spawning prior to migrating to Norwegian feeding grounds, and how much prey that were available and able to be utilized during the feeding seasons. This may also explain why my results show higher condition (K) for ABFT in Norwegian waters, compared to the condition (K) Percin and Akyol (2009) found for ABFT in the Mediterranean Sea. As we have seen, there can be several reasons for differences in condition (K) and length/weight relationships, but the main finding is that ABFT in Norwegian waters have good condition ($K > 1.5$) after feeding over a long period after spawning. This is likely to be caused by high food availability as they migrate to Norwegian waters explicitly to feed on a vast amount of prey (Tangen, 1999; Trenkel et al., 2014; Nøttestad et al., 2017a). It is difficult to compare the condition on ABFT in recent years compared to previous periods (1950's to 1980's), as there is a lack of historic data on condition (K) of ABFTs that visited the Norwegian coast (Nøttestad and Graham, 2004; ICCAT, 2018).

A significant difference in ages of ABFT was found between 2016 and 2018. The mean age decreased slightly every year from 2016 to 2018, which could indicate younger fish replacing older fish migrating to Norwegian waters. Minimum age was 6 years and a reduction in minimum age from 7 years in 2016 to 6 years in 2017 and 2018, further suggests an influx of new younger ABFT into Norwegian waters during each feeding season. Large sizes of ABFT was also documented in Skagerrak during a satellite-tagging project 2018, where Danish researchers successfully tagged 91 ABFTs, where most were estimated to be over 200 kg in weight (DTU Aqua, 2018). It is possible that with consistently large sizes and possibly some of the same age-groups migrating to the Northeast Atlantic year after year, some ABFT may exhibit homing behavior to Norwegian waters. More studies on this are however needed, to verify this hypothesis. It is difficult to compare age composition from 2016 to 2018 with historical data, due to limited number of analyzed fish for ageing during the period 1950 to 1970 (Nøttestad and Graham, 2004; ICCAT, 2018).

There was a drastic reduction in distribution and migration pattern of ABFT in Norwegian waters from 1965 and onwards when the Norwegian ABFT fishery gradually decreased (Nøttestad and Graham, 2004). Fewer year-classes were present in the catches and the average weight of ABFTs caught increased from < 100 kg in the 1950's to > 350 kg in the late 1970's, showing the year-by-year increase in size (Nøttestad and Graham, 2004). Based on my results, possibly several year-classes and size groups have been present recent years. Also, with younger fish down to 6 years of age migrating to the northeastern borders of their natural historic distribution in Norwegian waters, this suggests a healthy and growing population. An increase in biomass of the East Atlantic stock component is, furthermore, also substantiated by annual scientific evidence in recent years (ICCAT, 2014; 2015; 2016; 2017; 2018).

4.3 Abundance, migration pattern and distribution of ABFT in recent years

The significant increase in observations documented in recent years, indicates than an increasing number of ABFT are migrating to Norwegian waters every year, and is furthermore, evidence of an increase in the East Atlantic stock biomass. Bad weather conditions west of Bergen in late September 2018 were said by the licensed fishermen, to be the main reason for not fishing up their quotas. It is a very weather-dependent fishery, as they often are dependent on observing the ABFT visually at the surface in order to locate the schools before attempts to catch the ABFT can be made. Despite bad weather conditions and relatively few commercially targeted catches made in 2018, many observations were made this year.

ABFT caught south of 62°N from 2016 to 2018 were significantly longer (5 cm) than ABFT caught north of 62°N. This is in contradiction to historical results, showing a pronounced positive length-dependent migration pattern with increasing latitude in Norwegian waters (Hamre, 1961; Nøttestad and Graham, 2004). Based on historical trends where older (12-15 year) individuals migrated northwards of 62°N and younger (5-12 years) individuals migrated southwards (Hamre, 1961), one could expect that the same trends in migration pattern were occurring today. My results showed the opposite of the historical trends in migration pattern, where the oldest and longest individuals were caught south of 62°N. Based on the age-length key made from the age-determined individuals from 2016 and 2017 (Table 1), ABFTs with SFL 220 to 224 cm mostly belong to 9-10-year-old fish and ABFTs with SFL 225 to 229 cm mostly belong to 10-11 year old fish. This suggests that there were mostly 10-11-year-old ABFTs south of 62°N and 9-10-year-old ABFTs north of 62°N, during recent years. Historically, with ages from 5-12 years being mostly found south of 62°N, my results are not necessarily inconsistent with historical trends, but maybe there were a lack of representation of older (12-15 years) as well as younger (5-12 years) individuals in Norwegian waters or in the catches, in recent years. If there was a higher representation of older and younger individuals, then maybe we could have seen a similar trend in migration pattern today as in historical times. The fact that the majority of observations was made around 61°N, matches historical trends from 1963 and onwards in Norwegian waters, where the vast majority of ABFT was caught south of 62°N (Cort and Nøttestad, 2007). This was at a time when there was a decrease in the distribution and migration pattern coinciding with a decrease in stock-size (Hamre and Tiews, 1964; Cort and Nøttestad, 2007). Today, however, there is a clear trend of an increasing stock size (ICCAT, 2018), and it is therefore a promising sign for the development of the stock that the ABFT are returning to historically prevalent feeding grounds, and seasonally also expanding further north. More studies are needed to pinpoint the migration pattern of different size and age-groups within Norwegian waters.

This study shows that the range in distribution has also surpassed historically known ranges (Hamre, 1957), with the northernmost registered observation throughout history being made at 76.2°N, just south of Svalbard on September 29th, 2018. This observation was made by four fishermen onboard M/S "Ramoen" who have many years of experience at sea. They explained in a mail correspondence between them and IMR that they observed 3-4 individuals at 20 to

30 meters distance to the boat, moving very rapidly, making quick turns while barely breached the surface. This was of something they never had seen before and they excluded that it could be of porpoise, Atlantic white-sided dolphin (*Lagenorhynchus acutus*), white-beaked dolphin (*Lagenorhynchus albirostris*), other species of whale, shark, seal, or of other marine mammals that they were used to seeing. Moreover, weather conditions were very good, which would have made it easier for them to distinguish ABFT from potentially other species. They also reported that there were capelin and probably other schooling prey-species in the area, which furthermore indicates that they were witnessing ABFT feeding behavior. No scientific documentation such as pictures or videos were provided of this observation, but it was eventually deemed credible after the mail correspondence between them and scientists at IMR.

Today, ABFTs seem to both arrive and leave somewhat later (Table 5) than compared to 1950 to 1970's when the ABFT stayed from early July until late October (Nøttestad et al., 2017a). Jusup et al. (2011) argues that the Pacific bluefin tuna (PBFT) are poorly equipped to deal with starvation due to high energy demands in varying environments. This is likely to be applicable also to ABFT, which would not be likely to overwinter in cold arctic waters, if there were not enough amounts of prey available. In addition, knowing that the ABFT requires significant amounts of prey in maintaining growth and body temperature (Block and Stevens, 2001), it suggests that there must be good feeding conditions for ABFT in Norwegian waters, lasting even through the winter months.

4.4 Ecological impact of an increasing number of top-predators in Norwegian waters

The ABFTs visiting Norwegian waters and exhibiting feeding and hunting behavior seems to mainly prey on mackerel based on few available stomach samples at IMR. This is also substantiated by the results in this study, where some observers saw escaping juvenile mackerel during ABFT observations. However, this information should not be emphasized to much as only a few observations contained information about escaping prey. More specific research on stomach content should be conducted in the future.

Changes in predator abundance can impact the ecosystem resilience, structure and function (Paine, 1969; Duffy, 2002). There is evidence suggesting that large predators (such as ABFT) can have top-down cascading effects on the food web (Myers and Worm, 2003; Scheffer et al., 2005; Baum and Worm, 2009). ABFTs have a ferocious appetite, notoriously feeding on several species. They may be able to take out in the range of 100 000 tons of valuable pelagic species during one feeding season in Norwegian waters (Trenkel et al., 2014; Nøttestad et al., 2017a). The ecological effect of an increase in abundance of large ABFTs that can hunt together in large school-sizes up to 1000 individuals in Norwegian waters is, therefore, highly likely to have a significant impact on prey abundance as well as behavior. Maybe this could have indirect implications for the Norwegian commercial fishing fleet that targets mackerel, herring and other species that ABFT prey on. An increasing number of ABFT in Norwegian waters is also very likely to increase the risk of ABFT bycatches, especially considering that the ABFT prey on commercially targeted species, such as mackerel and herring, during the fishing season. Quotas set aside for bycatch have been increased for Norwegian fishermen to 28 tons in 2019. Also, with a total of six incidents where large ABFT penetrated through fish farm nets between 2016 and 2018, it is likely that an increase in abundance will increase the risk of this occurring in the future. The ABFTs are likely to have been attracted by the trout (*Oncorhynchus mykiss*) and salmon (*Salmo salar*) swimming inside the pens. However, an analysis of stomach content by one of the trapped ABFT was done by IMR staff during 2018, where the stomach was found to be empty. In other incidents workers on fish farms have observed salmon in their mouth and stomach, clearly showing that ABFT also feed on salmon inside the pens. More research should be conducted on how to prevent and prepare for this in the future, as the aquaculture industry should be better prepared for such incidents in the years to come.

Three observations were made of stranded dead ABFT in 2018, whereof two were made very late in the feeding season on the 22nd and 25th of December. One of these observations came from Nærøyfjorden, a small fjord branching of Norway's longest fjord, Sognefjorden. The cause of death was unknown for all three cases and two of them had visible skin damage on their body and head regions (Appendix F). Maybe these individuals also had penetrated into fish farms and managed to escape. Perhaps they were caught as bycatch and released back into the sea, or maybe they died of starvation or other natural causes. The New York Post also reported three separate strandings of ABFTs in Scottish waters during 2018, where one also occurred late in the year, on the 16th of December (Rodger, 2018). This indicates that the reasons for stranding of ABFT in Norwegian waters could be similar to those in Scottish waters, although the reasons are unknown. Fish strandings have been documented in the scientific literature but mostly of trout (*Salmo trutta*) and salmon and little of other fish species (Nagrodski et al., 2012). Strandings of solitary whales, are often thought to be due to severe disease or other interactions between physical (in e.g. current, coastline, temperature) and biological (in e.g. predatory pressure, food availability, disease) conditions (Cordes, 1982). Although speculative, these causes could also apply to the strandings of large solitary ABFT found in this study. If observations of stranded ABFT(s) is reported in the future, samples and analysis of stomach content should be conducted, to evaluate cause of death.

With a significant relationship found between size of school to time of year, we see that the ABFTs are changing their schooling behavior throughout a feeding season. There was a higher probability of encountering schools with more than 10 individuals from mid-September to mid-October. This finding has implications for the commercial ABFT purse seine fishery because it can help determine the best time to fish for ABFT to maintain best flesh quality. Studies have indicated that stressful practices can affect the flesh quality in fish (Lowe et al., 1993; Poli et al., 2005). Tenningen et al. (2012) showed that by targeting smaller schools of herring with purse seine, crowding densities can be reduced and thereby reduce stress to the fish. This is likely to be applicable also to purse seine catches of ABFT, and therefore, highly relevant in preventing destruction of flesh quality. This information should, therefore, be used when deciding how and when to fish for ABFT, although more research should be done to substantiate when the ABFTs swim in smaller and larger schools. More studies are needed to develop fishing practices and methods that are less stressful for the ABFT, to ensure flesh quality and maintain high economic value of the fish.

Another topic to be mentioned in relation to the near collapse and the recent return of ABFT in the Northeast Atlantic, is the potential effect of climate variation. Global rise in temperature has been suggested as a driver for dispersion and migration pattern of several species (LaRoe, 1995; Mason, 1995; Butler, 2003; Roessig et al., 2004). Cyclical changes in the environment can also alter migration pattern in fish (Hoar, 1953), and changes in temperature are associated with several phenotypic changes in fish such as changes in age at maturity, growth, survival, fecundity, age at juvenile migration and timing of migration and reproduction (Crozier and Hutchings, 2014). Faillettaz et al. (2019) argues that hydroclimatic variability strongly influences ABFT distribution, with warm and cold Atlantic Multidecadal Oscillation (AMO) affecting their spawning and migration. They argue that warmer water during the recent decade have resulted in increased areas of spawning as well as an increase in the distribution of the ABFT. With an increase in sea temperatures over the past decades compared to 1940's and onwards (Figure 22) it might play a part in the change of the migration pattern and distribution of the East Atlantic stock. The average decadal SST and temperatures from 200 meters depth in Sognesjøen from July to October, have increased with about 2°C for SSTs at 10 meters depth and 0.5°C at 200 meters depth since 1940's (Figure 22).

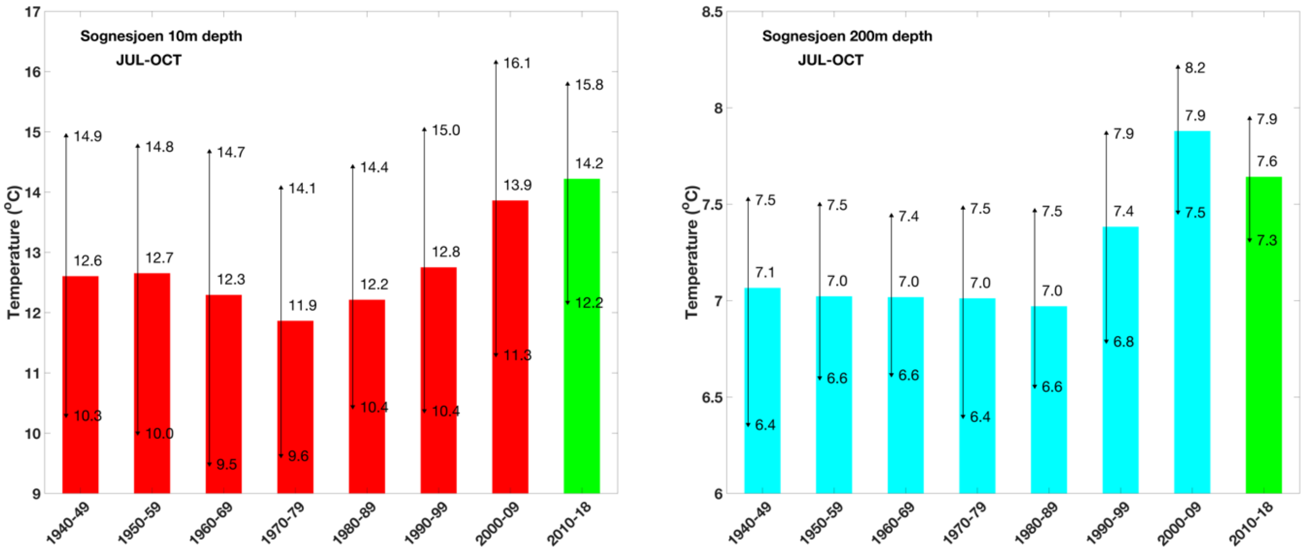

Figure 22: *Average decadal water temperatures at 10m depth (left) and at 200m depth (right) with minimum, mean and maximum temperatures from July to October each decade from 1940 to 2018, from IMR's hydrographical station in Sognesjøen. Minimum and maximum temperatures are shown with 10- and 90 percentiles, respectively. Provided by Jon Albretsen at IMR.*

Perhaps global rise in temperature have been a main cause for the ABFT to return to Norwegian waters. With their endothermic physiology, ABFTs can sustain warm (up to 30°C) and cold (down to 3°C) water temperatures and maintain a higher body temperature than surrounding water temperatures (Block et al., 2001; Block and Stevens, 2001). It is therefore, thought to enable them to expand their habitat into areas with colder water temperatures such as in the Northeast Atlantic (Carey and Lawson, 1973; Neill et al., 1974; Block and Finnerty, 1994; Block and Stevens, 2001; Graham and Dickson, 2004). The water temperature registered for the observation made south of Svalbard during 2018, was 3.5°C at the surface. This is, moreover, the same water temperature that one of the ABFT individuals that was tagged during the satellite tagging project in 2018, experienced while diving to 487 meters depth (Ferter et al., 2018). This suggests that even very cold water temperatures such as 3.5°C are not a physiological problem for the ABFT for survival and their pursuit for food. Nøttestad and Utne (2016) argue that limited available food resources were a main reason for the expansion of Northeast Atlantic mackerel in recent years. The same principles could apply to the recent expansion of ABFT into Norwegian waters. Also, with mackerel being an important source of food for ABFT in Norwegian waters (Nøttestad et al., 2017b), it could well be that the expansion in the migration of mackerel in recent years, have impacted the migration of ABFT where it follows the same migratory movements of its prey (MacKenzie et al., 2014). With an increase in stock size over the last decade, an increased need for prey is probably a major driving force for the recent return of ABFT into Norwegian waters (Nøttestad et al., 2017a) but we cannot rule out that an increase in water temperatures also have had an impact (MacKenzie et al., 2014). More studies on the effect of rising water temperatures on the migration pattern of ABFT should be conducted. Itoh et al. (2003) showed that the horizontal distribution of small PBFT mostly occurred in water temperatures between 14°C and 20°C. Seeing that tunas exhibit water temperature preferences, water temperature should be collected during the Norwegian ABFT fishery in the future to be used as a proxy for distribution.

4.5 Possible reasons for the near collapse and recent recovery of the population

From 1950 to 1962, there were several year-classes of ABFT present in Norwegian waters. These are thought to have been year-classes from the early 1940's. These year-classes gave rise to good fishing opportunities for ABFT all along the Norwegian coast up to 71°N (Hamre and Tiews, 1964; Nøttestad and Graham, 2004) and as there were no historical regulations or restricted quotas for the ABFT fishery until the early 1980's in the Atlantic Ocean, there were unlimited opportunities for practically everyone who wanted to fish for ABFT (ICCAT, 2018). As a result of the high fishing pressure on several year-classes during this period, by the early 1960's the fishery decreased in range with most catches occurring south of 62°N, fewer fish were caught and fewer year-classes were present in the catches. From 1956 and onwards to the cease of the fishery in the late 1970's to mid-1980's, the Norwegian fishery mostly relied on two strong year-classes from 1950 and 1952 (Hamre and Tiews, 1964). In addition to possible overfishing inside Norwegian waters, there was a massive overfishing of juveniles from 1949 to 2010 (Cort and Abaunza, 2016), leading to considerable growth overfishing leaving very few fish to grow older and migrate to Norwegian waters during the feeding season (Nøttestad and Graham, 2004; ICCAT, 2018). With little replenishment of the stock along with overfishing of both juvenile and large mature individuals in the Northeast Atlantic, the near collapse of the stock was inevitable.

The year-by-year increase in observations of ABFT in the Northeast Atlantic, shown in this study, as well as the increase in stock biomass of the East Atlantic stock (ICCAT, 2018), has likely been a result of implementation of strict regulations after the 1980's and proper management afterwards and until present date. Today, ABFT has probably one of the strictest fishing regulations in terms of substantial control at sea and in port, of all fish species on the planet (ICCAT, 2018). Regulations like minimum landing size, limitations of number and size of vessels, limited quotas as well as limited fishing areas and periods in addition to increased control at sea and in port, is therefore likely to have been crucial in recovering and rebuilding the ABFT population (ICCAT, 2018). Management measures introduced in the Northeast Atlantic from 1970's and onwards, have also shown to be crucial for the recovery of two previously overfished fish stocks; the Norwegian spring-spawning herring and Northeast Arctic cod (*Gadus morhua*) (Nakken, 2008). This shows that proper fisheries management can be of significant importance for the recovery of several fish stocks.

4.6 Implications for present stock assessment and management

The larger fish in a population normally contributes more to spawning success and increased reproduction than smaller individuals (Hixon et al., 2013). The large ABFT visiting the Norwegian coast can also utilize its growth potential in highly productive Norwegian waters (Huse et al., 2012; Nøttestad et al., 2017a), and has a far better ability to take advantage of larger feeding areas further away from spawning sites compared to smaller individuals (Nøttestad et al., 2017a). With this study providing substantiating evidence for an increase in abundance of large ABFT in good condition ($K > 1.5$) into Norwegian waters, it supports that the Norwegian ABFT fishery can take maximum advantage of their growth potential, feeding opportunities, size composition, fish quality and revenue (Nøttestad et al., 2017a). Depending on future stock assessment and management, it is likely that we will witness a further expansion of the Norwegian ABFT fishery in the years to come. However, with experience from historic overfishing, increased exploitation can alter the age structure of fish stocks (Nøttestad and Graham, 2004; Brunel, 2010), and it is important to conserve the oldest and largest individuals to prevent truncation of size and age structure of the population (Hixon et al., 2013). It is, therefore, especially important to avoid overexploitation of the predominantly large and old ABFT that migrates to Norwegian waters, to maintain a healthy and varied age structure of the population.

Stock management should consider that mixing occurs between the East Atlantic and the West Atlantic stock (Rooker et al., 2008a; Rooker et al., 2008b; Galuardi et al., 2010; Rodríguez-Ezpeleta et al., 2017). High exploitation rates in the Mediterranean and the East Atlantic have, based on the level of mixing between the stocks, been suggested to impair the recovery of the West Atlantic stock previously (NRC, 1994). Secor et al. (2015) suggested that juveniles from the West Atlantic stock that migrated into the Northeast Atlantic and Mediterranean, where they encountered higher rates of exploitation, could be a reason for the depressed abundances of the West Atlantic stock after intense overfishing occurred in the 1970's. Also, with tunas in general, being an important source of food and income for both developed and developing countries, some stocks have been subject to high exploitation rates for decades (Collette et al., 2011; Juan-Jordá et al., 2011). Pons et al. (2017) showed that stocks with high commercial value were more depleted, particularly tunas. With ABFT being a highly economically valuable fish species (Fromentin and Powers, 2005) it has been subject to illegal and unreported fishing in recent years (Agnew et al., 2009). Illegal and unreported fishing of ABFT may therefore pose a threat for the stock in the future and should be taken into consideration by stock management. For a sustainable future fishery, management should continue to have annual revisions of the East Atlantic stock, with attention on the spawning potential and recruitment of the stock, when establishing annual quotas. It is also important that future management of both the West and East Atlantic stock, take into consideration potential impacts that the ABFT management may have on other fisheries. As we have seen, managing a highly migratory species where individuals mix between populations is not straight forward. Galuardi et al. (2010) argued that with evidence of ABFT being a metapopulation, it should be treated as such, with a more spatial explicit approach of management. In addition to evidence for mixing between the West and East Atlantic stock (Rooker et al., 2008a; Rooker et al., 2008b; Galuardi et al., 2010; Rodríguez-Ezpeleta et al., 2017), Riccioni et al. (2010) proposed that there could be more than three populations of ABFT. However, with evidence from recent electronic tagging studies showing that there are indeed two principal spawning areas, this supports the two-stock management approach by ICCAT (Stokesbury et al., 2004; Block et al., 2005; Teo et al., 2007; Aranda et al., 2013; Rodríguez-Ezpeleta et al., 2017).

4.7 Conclusion and suggestions for further research

This thesis shows a clear annual increase in numbers of large ABFT in good condition (K), migrating to Norwegian waters from 2012 to 2018. A decrease in mean age from 2016 to 2018, has also been shown, suggesting several year-classes migrating to Norwegian waters. We have also witnessed seasonal increase in the latitudinal distribution, and an indication of increased duration of stay compared to historical periods. The major driving force behind the recent return of ABFTs into Norwegian waters is likely to be due to an increased need for prey as a result of an increase in stock biomass. However, increase in water temperature over the last decades cannot be ruled out to have made an impact on the migration pattern of ABFT. Depending on future development and recruitment of the stock along with sustainable management practices, it is likely that we will continue to observe and catch ABFT in Norwegian waters in the years to come. Higher abundances of ABFT in Norwegian waters are likely to increase bycatches of ABFT, affect prey abundance and behavior, and increase the likelihood of individuals penetrating through fish farm nets. Moreover, an increasing number of ABFT in Norwegian waters have resulted in a reestablishment of the historical fishery which is likely to increase in the years to come, also depending on the development of the stock. With higher chances of observing larger schools during mid-September to mid-October, fishermen could use this information to determine when to fish for smaller schools of ABFT, to ensure quality of the flesh and to maintain maximum value of the fish. Some ABFT could be exhibiting learning and homing behavior to Norwegian feeding grounds, since we consistently document large and old size-groups coming year after year. Management of the East Atlantic stock should take into consideration the spawning potential and recruitment of the stock, the age structure of the stock, the ecological impacts of an increasing number of ABFT into Norwegian waters, illegal and unreported fishing and also the potential impact management of the East Atlantic stock can have on other fisheries governed by other countries, as well.

More studies on abundance, distribution and general biology regarding catch sizes and individual sizes are needed. Multibeam sonar recordings have shown to be a useful fishery-independent tool for providing indices of abundance of ABFT (Melvin, 2016; Uranga et al., 2017). With the ability to monitor and quantify high volumes of data at relatively low costs, (Uranga et al., 2017), multibeam sonars could be a useful tool for future abundance estimates of ABFT in Norwegian waters. More studies on developing and using multibeam sonar recordings for indices of abundance of ABFT in Norwegian waters, should be conducted.

Environmental factors could also have caused changes in migration pattern of the ABFT directly (Faillettaz et al., 2019), or indirectly by changing migration pattern of distinct species that the ABFT feed on. Information of what they feed upon can therefore, be relevant in understanding why they migrate to various locations. For further research, analysis of ABFT stomach content should be performed. Using pop-off satellite tags can be a very precise and accurate method of measuring the migration pattern, along with temperatures at different depths of ABFT (Block et al., 1998). A continuation of the satellite tagging project should therefore be conducted in Norway in coming years.

Even though positions of observations of ABFT and commercial catch data were collected in this study, there was not enough reliable data to determine the location of the arrival of ABFT during recent years. Nor was there enough data to establish which size groups that were arriving first into Norwegian waters during recent years. With an increasing Norwegian commercial quota for ABFT in following years, these types of questions should be studied in the future, based on data such as; position and time of catch and size of individual ABFT.

A comparison between commercial and recreational fishery on ABFT in Norway should be conducted in the future with a focus on the selectivity pattern between the different capture methods in each type of fishery. Norway had historically a CPUE index on ABFT from the commercial fishery for 10+ year old fish from 1954 to 1980 used as an abundance index in ICCAT (Nøttestad et al., 2017b; ICCAT, 2018). It is possible to gain access to these historical data and compare to present commercial CPUE indices. By looking at CPUE indices between commercial and recreational fishery, a first insight about efficiency between the time-series can be made. This information can be used as a concept for future studies and evaluation.

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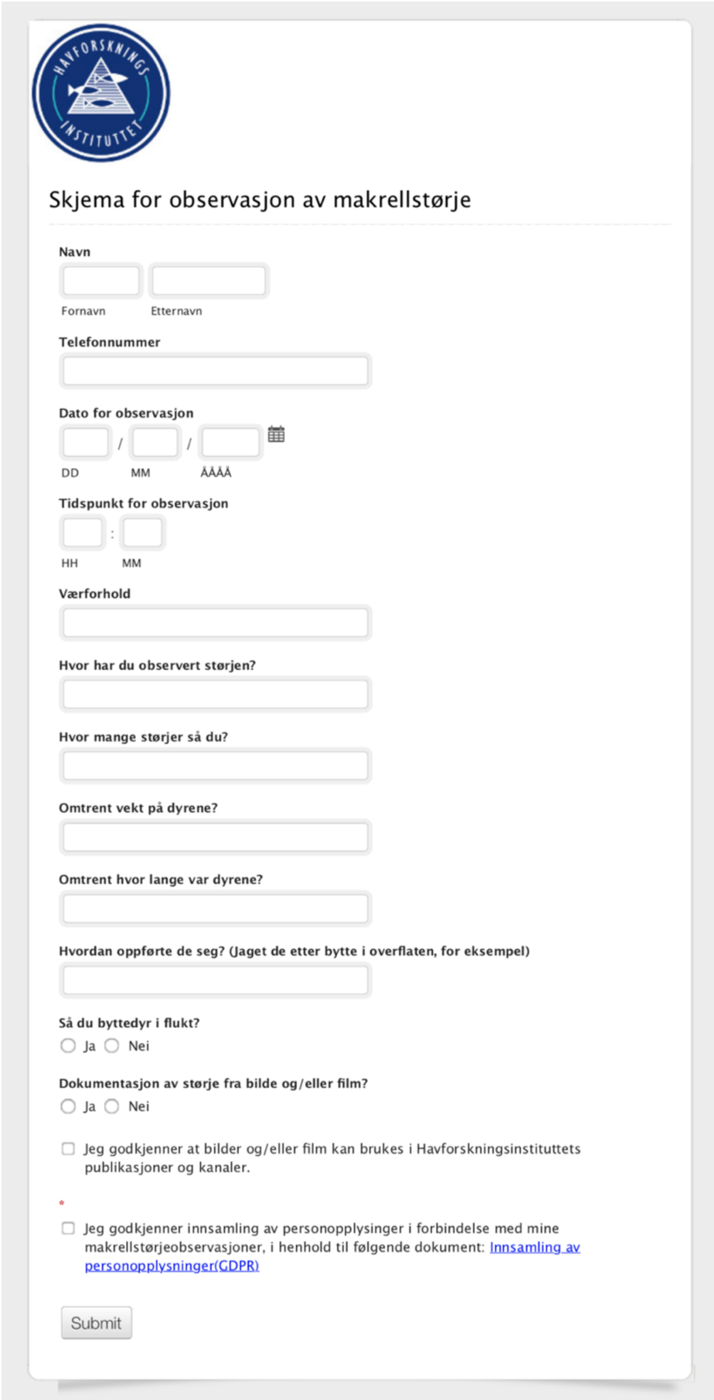
6. Appendices

Appendix A: Conversion factors used for weight

Table I: *Showing state of fish before weighing with corresponding conversion factors for ABFT caught in Norwegian waters during 2016 to 2018, suggested by the Norwegian Directorate of Fisheries 2018. Provided by Rune Paulsrud Mjørlund at the Norwegian Directorate of Fisheries.*

State of fish before weighing	Conversion factor
Gutted with head but removal of operculum	1.17
Gutted with head, gills are removed	1.16
Gutted with head without tail, gills are removed	1.19
Gutted without head	1.28

Appendix B: Online observational registration from



Skjema for observasjon av makrellstørje

Navn

Fornavn Etternavn

Telefonnummer

Dato for observasjon

DD / MM / ÅÅÅÅ

Tidspunkt for observasjon

HH : MM

Værforhold

Hvor har du observert størjen?

Hvor mange størjer så du?

Omtrent vekt på dyrene?

Omtrent hvor lange var dyrene?

Hvordan oppførte de seg? (Jaget de etter bytte i overflaten, for eksempel)

Så du byttedyr i flukt?

Ja Nei

Dokumentasjon av størje fra bilde og/eller film?

Ja Nei

Jeg godkjenner at bilder og/eller film kan brukes i Havforskningsinstituttets publikasjoner og kanaler.

*

Jeg godkjenner innsamling av personopplysninger i forbindelse med mine makrellstørjeobservasjoner, i henhold til følgende dokument: Innsamling av personopplysninger(GDPR)

Submit

Figure I: *Online observational registration form made by IMR specifically for this project.*

Online link:

http://mform.imr.no/view.php?id=83147&fbclid=IwAR1tBM6Z7sz_EGoLE7NOMYIPMXhhCsqLb7YqN8fpD-zVEipjV-p8MXB2Eh8

Appendix C: Questionnaire sent out to Facebook groups

Vi er på jakt etter dine observasjoner av makrellstørje!

Hei!
Jeg er med i et prosjekt for Havforskningsinstituttet i Bergen der vi er på jakt etter tilgjengelige data av observasjoner av makrellstørje/blåfinnet tunfisk i norske farvann som dere kan ha gjort fra 2013-2018. Dette vil bidra i kartlegging av vandringsmønsteret til størjen i lag med å gi oss ellers nyttig informasjon rundt å forklare tilbakekomsten av makrellstørje i våre farvann!

Flott om dere vil bidra til spennende forskning ved å sende følgende opplysninger til
erling.boge@hi.no
eller ring Tlf: 45675165

- *Dato for observasjon*
- *Foto/video*
- *Posisjon (hvor har du observert størje?)*
- *Ca str på stim/stimer og ca antall størje.*
- *Ca str på individ (hvor lang?)*
- *Tidspunkt / klokkeslett*
- *Værforhold*
- *Atferd (eks; jagende etter byttedyr)*
- *Eventuelle byttedyr som kan ha prøvd å flykte*

Mvh Erling Boge

Appendix D: Pictures retrieved from commercial catches, bycatches and from fish farms

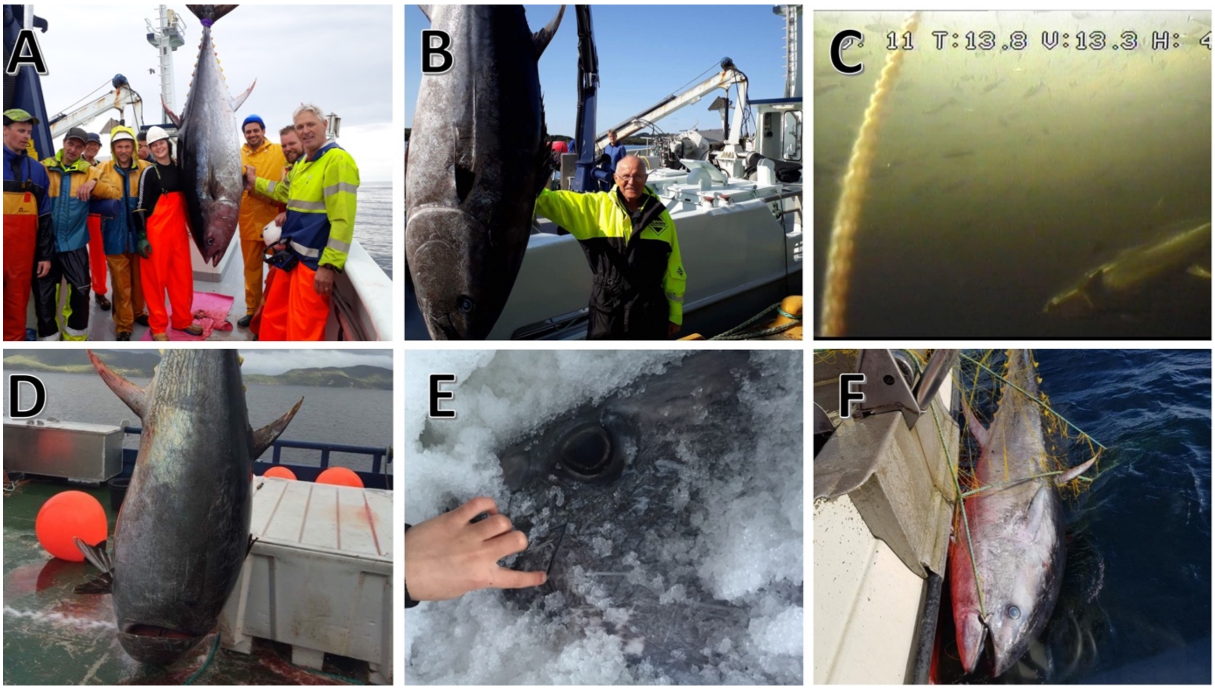


Figure II: *A) Crew of M/S "Bluefin" with an ABFT caught in the directed fishery during the fishing season in 2017. Photo: M/S "Bluefin". B) Crewmember of M/S "Bluefin" with a very large ABFT caught in the directed fishery during the fishing season in 2017. Photo: M/S "Bluefin". C) Picture of a 286 kg ABFT inside one of K. Strømmen lakseoppdrett AS's fish pens in Bremanger during 2018. Photo: K. Strømmen lakseoppdrett AS. D) and E) A 245 kg ABFT that got trapped in a fish farm in Kvalvåg, Frei outside Kristiansund in 2016. It was approved for human consumption by a veterinary and then sold to a buyer in Oslo. In picture E) it is being cooled down with ice in preparation for transport to Oslo. Photo: Ørjan Dyrnes. F) A large ABFT caught as bycatch in an anglerfish gillnet which was set at 100m depth outside Frøya in Trøndelag. A large angle/hook was seen in its mouth, but not one thought to be selected for bluefin tuna. The photo was taken on 11.09.2018. Photo: Terje Melkvik.*

Appendix E: Pictures retrieved if different types of acoustic recordings of ABFT and possible prey fish of ABFT.

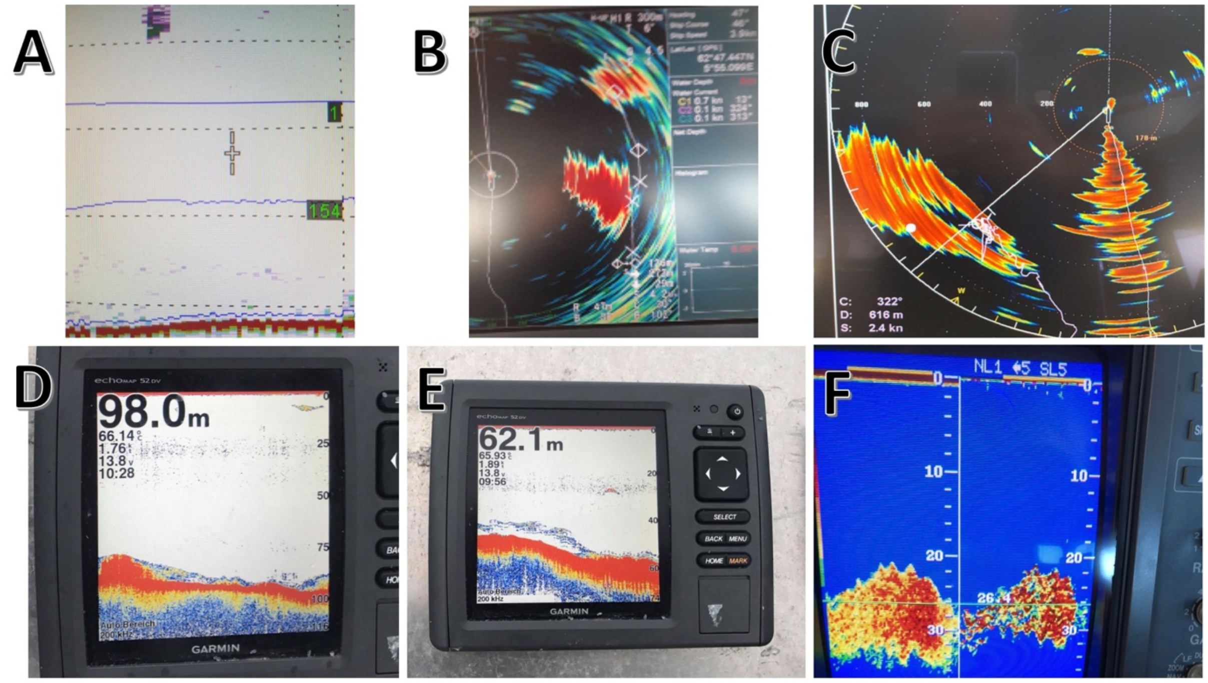


Figure III: *A) Echo-sounder showing what is likely to be of one single ABFT. Photo: M/S "Bluefin". B) Picture from September-October 2017, of sonar showing several schools of what is likely to be ABFT. The largest red dot was estimated by fishermen to consist of 400-500 ABFT. Photo: M/S "Bluefin". C) Picture from 03.10.18 of sonar showing large magnitudes of ABFT and several species of whale, all feeding on mackerel just outside the Norwegian EEZ (62.16°N, -0.5°E). Photo: Ole Inge Møgster. D) Picture from 2017 of an echo-sounder showing what is likely to be of one ABFT close to the surface in the top right side of the picture. This tuna was estimated to be 350-400 kg by the fisherman who made the observation. This observation was made together with a visual observation of a few ABFT in the surface. Photo: Enrico Wyrwa. E) Picture from 22.09.2017 of an echo sounder showing what is likely to be of one ABFT in the middle of the water column between 20- and 40-meters depth. This observation was made together with a visual observation of a few ABFT in the surface. Photo: Enrico Wyrwa. F) Picture from 06.10.2018 of an echo-sounder showing what can be schooling prey fish of ABFT or ABFT. Visual observations of ABFT at the sea surface was made in the same area when the photo was taken. Photo: M/S "Bluefin".*

Appendix F: Pictures retrieved of three stranded ABFTs during 2018

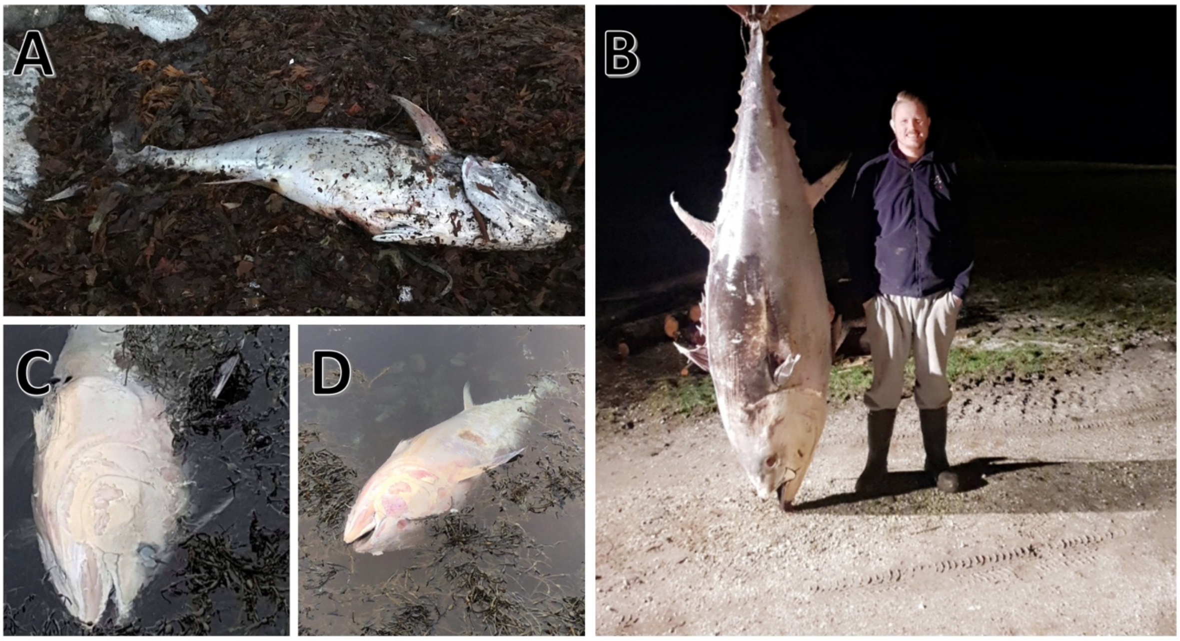


Figure IV: *A) Picture of one stranded ABFT on a beach at Husøya, Ona 27.10.2018. Photo: Tore Viken. B*) *Picture of stranded ABFT observed on the shoreline in Nærøyfjorden 25.12.2018. Here it is being lifted up by a tractor. The person next to the fish is 186 cm tall. Photo: Terje Stalheim. C)* and *D) One stranded ABFT observed in Fjaler, Hellevik on 22.12.18. Picture D) is showing the same ABFT but the picture was taken approximately one week later than picture C). Photo: Christer Rambjørg.*

Appendix G: Pictures of classic behaviour of ABFT hunting at the surface

The pictures in Figure 4 show examples of what visual observations of ABFT hunting at the surface, can look like.

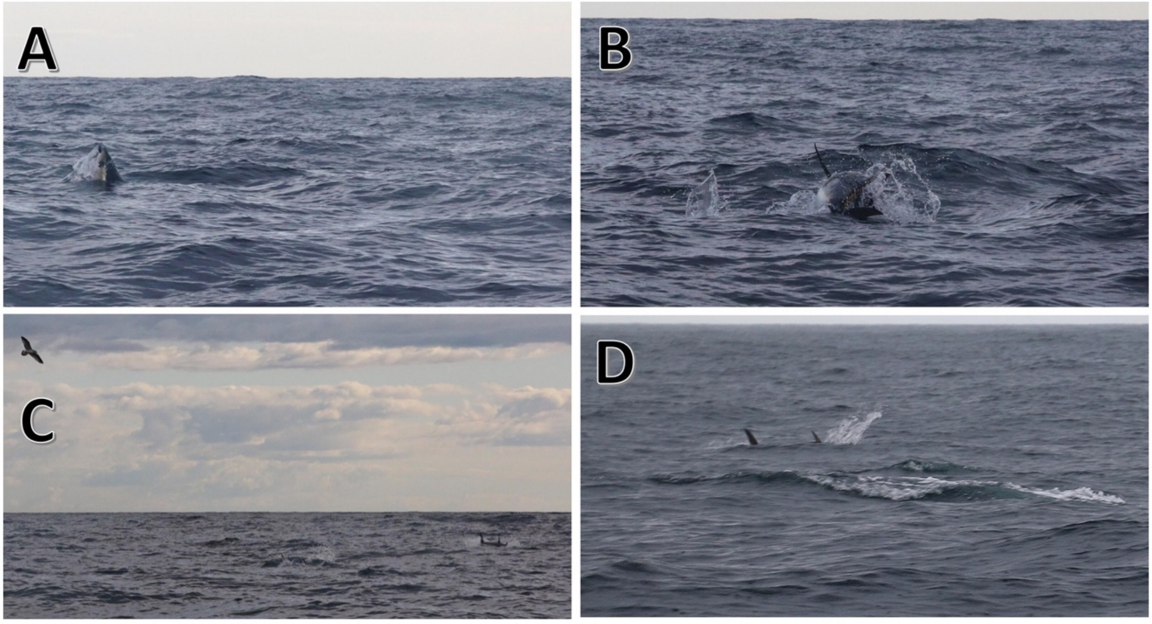


Figure V: *Pictures A), B), C) and D) showing classic behavior of ABFT hunting at the surface, where they often breach the surface during quick pursuits after prey. All photos: Endre Hopland.*

Appendix H: Examples of additional observations that weren't registered

The following sections provide examples of additional information provided for some observations where only one or a few observations were registered in this study:

Example of additional comments made about observations 2017

One observation was registered from the 10th September 2017, of 4-5 schools consisting of 50-500 ABFTs hunting juvenile mackerel, observed by M/S "Bluefin". In addition to this observation and a few more registered from M/S "Bluefin", the captain on the boat provided information of many more observations made by them during 2017. They frequently observed ABFT when they went to and from the mackerel fields, both visually and on sonar. They observed several large schools estimated to consist 600-800 large (+250kg) ABFT in the time period 20th September to 25th October 2017, as well as several smaller schools consisting of 20-150 ABFT, throughout the fishing season. Most observations were made north of 62°N and around 5 to 6°E.

One observation was registered from the 2nd October 2017, of a small school seen in Frøya, observed by a recreational fisherman. In addition to this observation, the observer explained that from the 6th August to 2nd October, he had 18 trips out at sea, where he observed small schools of ABFT on all of these trips.

Example of additional comments made about observations 2018

For most observations made on sonar and of commercial fishing vessels during 2018, it was a lot of additional information about sightings of more ABFT than what was registered in this study. M/S "Salvøy" and M/S "Hillersøy" did in some cases, observe bluefin tuna regularly when only one or a few observations were registered.

I heard about several more people who had made observations from 2016 to 2018. Due to difficulties in getting in contact with the observers and having them register their observations, I decided not to spend too much time at retrieving every single observation that was mentioned, as I already felt I had representable amounts of observations registered to work with.