

# Atlantic bluefin tuna: population dynamics, ecology, fisheries and management

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## Abstract

Both old and new information on the biology and ecology of Atlantic bluefin tuna have confronted scientists with research challenges: research needs to be connected to current stock-assessment and management issues. We review recent studies on habitat, migrations and population structure, stressing the importance of electronic tagging results in the modification of our perception of bluefin tuna population dynamics and behaviour. Additionally, we question, from both scientific and management perspectives, the usefulness of the classical stock concept and suggest other approaches, such as Clark's contingent and metapopulation theories. Current biological information confirms that a substantial amount of uncertainty still exists in the understanding of reproduction and growth. In particular, we focus on intriguing issues such as the difference in age-at-maturity between West Atlantic and Mediterranean bluefin tuna. Our description of Atlantic bluefin tuna fisheries places today's fishing patterns within the two millennium history of exploitation of this species: we discuss trap fisheries that existed between the 17th and the early 20th centuries; Atlantic fisheries during the 1950s and 1960s; and the consequences of the recent development of the sushi–sashimi market. Finally, we evaluate stock status and management issues since the early 1970s. While important uncertainties remain, when the fisheries history is confronted with evidence from biological and stock-assessment studies, results indicate that Atlantic bluefin tuna has been undergoing heavy overfishing for a decade. We conclude that the current exploitation of bluefin tuna has many biological and economic traits that have led several fish stocks to extreme depletion in the past.

**Keywords** Atlantic bluefin tuna, population dynamics, population structure, stock assessment and management, *Thunnus thynnus*, tuna fisheries

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## Introduction

Atlantic bluefin tuna (*Thunnus thynnus*, Scombridae) have fascinated scientists and philosophers for centuries, starting with the ancient Greek and Latin philosophers (Aristotle and Pliny the Elder) and continuing with many scientists since the end of the 18th century. This fascination comes from striking biological properties, such as an impressive size (>3 m and up to 900 kg) and a swimming speed which allows extensive migrations between cold temperate feeding grounds and warm waters spawning grounds. The Atlantic bluefin tuna (ABFT) has also been of great economic interest, as been continually and significantly exploited in the Mediterranean Sea for thousands of years (Mather *et al.* 1995; Doumenge 1998). Presently, ABFT is back in the limelight, as fishing for it has become a highly profitable activity particularly with the development of the sushi-sashimi in Japan. This new market opportunity has increased the demand for high-quality fish, stimulating the market to attain some very high prices in recent years. For example, a single bluefin tuna was sold for 174 000 US\$ in 2001 at the Tokyo market. This new situation has inevitably induced tension between various fishing entities, including fishermen, national and international administrations, national scientists and NGOs (Fromentin and Ravier 2005; Porch 2005).

While remarkable changes have occurred in the exploitation of ABFT during the last two decades, research activities have also been vigorous during

that period. The physiology, biology and behaviour of this species is somewhat better understood. For example, as ABFT is a pelagic fish that never stops swimming to ventilate (like other tunas and some sharks), it continuously generates heat which is used to elevate and maintain muscle, eye, brain and visceral temperatures above water temperatures. This property of endothermy is highly developed in ABFT and contributes to its extensive capacity for migration (for a recent review see Graham and Dickson 2001). Also, our perception of population and spatial dynamics has been strongly modified by recent studies on biology and ecology of ABFT (e.g. Humston *et al.* 2000; Ravier and Fromentin 2001; Medina *et al.* 2002; Rooker *et al.* 2003; Carlsson *et al.* 2004; Royer *et al.* 2004), electronic tagging experiments (e.g. see Lutcavage *et al.* 2000; Block *et al.* 2001; Gunn and Block 2001) and new modelling approaches (Punt and Butterworth 1995; Porch *et al.* 2001).

Nevertheless, linkages between advances in biology and ecology of ABFT and current developments in fisheries biology, exploitation and management are still lacking. The last extensive review of ABFT was published by Mather *et al.* (1995). Note that despite the relatively recent date of publication, this review was prepared during the 1970s (more than 25 years ago). Nevertheless, it remains a key reference. Thus, there is a need to examine more recent research activities. The purpose of this article is to review key information on ABFT (both old and new) and to link major research results with stock assessment and management challenges, in order to

provide an overall characterization of this species and its exploitation.

## Ecology and population structure

### Habitat

Atlantic bluefin tuna inhabit the pelagic ecosystem of the entire North Atlantic and its adjacent seas, primarily the Mediterranean Sea (i.e. from the equator to the North of Norway and from the Black Sea to the Gulf of Mexico; Mather *et al.* 1995). Among the tuna, ABFT has the widest geographical distribution and is the only large pelagic fish living permanently in temperate Atlantic waters (Bard *et al.* 1998; Fromentin and Fonteneau 2001). Archival tagging and tracking information confirmed that ABFT can sustain cold (down to 3 °C) as well as warm (up to 30 °C) temperatures while maintaining stable internal body temperature (Block *et al.* 2001). Until recently, it was assumed that ABFT preferentially occupies the surface and subsurface waters of the coastal and open-sea areas, but archival tagging and ultrasonic telemetry have changed our perception. While ABFT appear to primarily reside in surface waters, both juvenile and adult ABFT frequently dive to depth of 500–1000 m (Lutcavage *et al.* 2000; Block *et al.* 2001; Brill *et al.* 2001). Similar behaviour has also been reported for southern bluefin tuna, bigeye tuna and swordfish and is generally related to foraging in deep scattering layers and/or to physiological constraints to cool the body temperature (Carey and Robinson 1981; Holland *et al.* 1992; Bard *et al.* 1998; Gunn and Block 2001; Musyl *et al.* 2003). These results make clear that the habitat of ABFT cannot be solely described in two dimensions (Brill and Lutcavage 2001; Wilson *et al.* 2005).

The spatial distribution and movement of ABFT are hypothesized to be controlled by preferential ranges and gradients of temperature (e.g. see Roffer 1987), similar to Pacific bluefin and other tuna species (Laurs *et al.* 1984; Lehodey *et al.* 1997; Bard 2001; Inagake *et al.* 2001). However, ABFTs high vertical mobility makes this species less likely to detect horizontal thermal gradients (as vertical temperature gradients are much larger than horizontal ones, see Brill and Lutcavage 2001; Brill *et al.* 2001). More recent work appears to converge toward the opinion that juvenile and adult ABFT frequent and aggregate along ocean fronts (Huston *et al.* 2000; Lutcavage *et al.* 2000; Royer *et al.*

2004). This association is also likely to be related to foraging, ABFT feeding on the abundant vertebrate and invertebrate prey concentrations of these areas (e.g. Boustany *et al.* 2001; Brill *et al.* 2001). The types of ocean fronts known to be frequently visited by ABFT are upwelling areas (such as the West coasts of Morocco and Portugal) and meso-scale oceanographic structures associated with the general circulation of the North Atlantic and adjacent seas (e.g. the East coast of North America from Cape Hatteras to the Gulf of St Lawrence, the Bay of Biscay and the northwestern Mediterranean; Farugio 1981; Mather *et al.* 1995; Bard *et al.* 1998; Boustany *et al.* 2001; Wilson *et al.* 2005). Despite this general agreement, the habitat of ABFT appears more complex than what could be explained by these oceanic features, alone, and much more remains to be learned (Royer *et al.* 2004; Schick *et al.* 2004).

### Migration and stock delimitation

Intrigued by the seasonal appearance of ABFT in various parts of the Mediterranean Sea, the ancient Greek and Latin philosophers, Aristotle (4th Century BC) and Pliny (1st Century AD), speculated that ABFT migrate close to the coasts by keeping the shore on their right and so, perform a large anti-cyclonic movement all around the Mediterranean. A migratory connection between oceans was first mentioned by Cetti (1777), who suggested that ABFT come into the Mediterranean from the North Atlantic to spawn around Sicily (either by following the North African or the European coasts) and then go back (by the same routes). Through observation of Italian trap fisheries, Pavesi (1889) disagreed with Cetti and postulated the occurrence of a separate Mediterranean ABFT stock. Surprisingly, his hypothesis, known as the 'native hypothesis', remained dominant for several decades and was accepted by several authors (e.g. Roule 1917; de Buen 1925; Scordia 1938). The native hypothesis was finally questioned when some hooks used in the North Atlantic (which were sufficiently different from the ones used in the Mediterranean) were found on fish caught in the Mediterranean (Heldt 1929; Sella 1929). Migration between the Mediterranean and North Atlantic was definitively accepted during the 1960s and 1970s based on a large set of recaptures of conventional tags (see Stock Status and Management or Sara 1963; Mather *et al.* 1995).

Migration between the North Atlantic and the Mediterranean has been documented by many observations since then. These observations have also led to the hypothesis that ABFT display a homing behaviour, i.e. ABFT migrate to spawn in specific and well-defined areas (Fig. 1). This hypothesis is supported by the most extensive electronic study published to date (Block *et al.* 2005), which tends to support spawning site fidelity in both the Mediterranean Sea and the Gulf of Mexico. Furthermore, ABFT distribute themselves over a wide habitat (probably at a rather low density), so that aggregation of individuals at any given time and place appears necessary to ensure mating and reproduction success of the population (e.g. Sinclair 1988). Ecologists usually distinguish between natal homing (a strict fidelity to the birth location due to imprinting of environmental cues

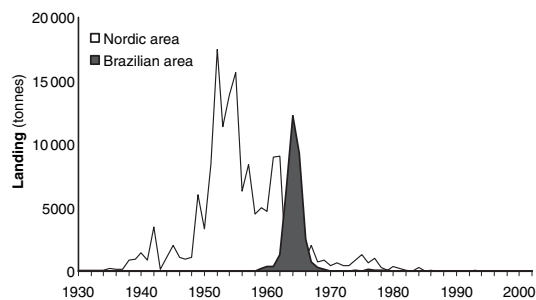
during early life stages, such as salmon, Cury 1994; Dittman and Quinn 1996) and repeat homing (a process related to spatial learning of the younger ones from the older individuals, Dodson 1988). Dodson (1988) and McQuinn (1997) also argued that spatial learning would be advantageous when fish can repeat experiences (i.e. iteroparous reproduction) and when they live in unstable and unpredictable environments (such as oceanic ones where the probability of recruitment failures are high). Conversely, imprinting would be beneficial to a semelparous reproductive strategy (e.g. salmon), especially in relatively stable environments (such as rivers). So in theory, ABFT is more likely to perform repeat homing, which is in further agreement with several observations and findings. Indeed, the schools of migrating spawners include a broad range of individual sizes (and ages)



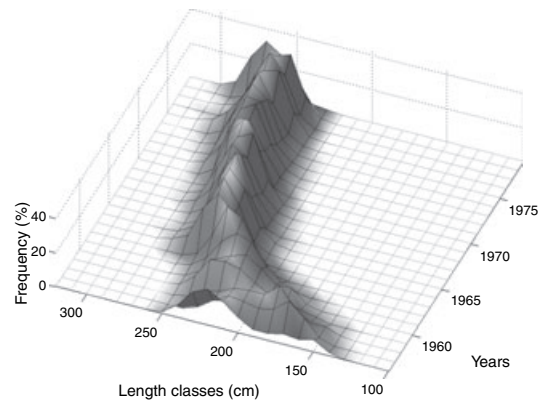
**Figure 1** Spatial distribution of Atlantic bluefin tuna (gray shading) and main migration routes (black arrows) are deduced from current and historical fisheries data as well as traditional and electronic tagging information (see text for references). The vertical dashed dotted line depicts the stock delimitation between the two current ICCAT management units. The main spawning grounds (dark dotted gray areas) being currently assumed in the literature are located in the Mediterranean Sea and the Gulf of Mexico.

and their quantity seems to fluctuate in relation to environmental conditions (Ravier and Fromentin 2004). Furthermore, past works have mentioned other spawning locations than are believed to occur today (see also the Reproduction), which could be due to the disappearance of some spawning habitats or to shifts of preferences for some areas to others.

Little is known about feeding migrations within the Mediterranean and the North Atlantic, but results from electronic tagging indicated that migration and movement patterns of ABFT vary considerably between individuals, years and areas (Lutcavage *et al.* 1999, 2001; Block *et al.* 2001; de Metrio *et al.* 2002). The appearance and disappearance of past fisheries also suggest that important changes in the spatial dynamics of ABFT may be environmentally driven (Marsac 1999; Ravier and Fromentin 2004). After examining size composition of the ABFT catches of the Norwegian and German fisheries, Tiews (1978) postulated that the sudden collapse of these fisheries in 1963 resulted from a lack of migrating mature tunas in the northern area (Fig. 2). Indeed, the mean size of ABFT caught by the Norwegian fleet continuously increased after the collapse of fishing in 1963. The size composition of the catch included fish from 140 to 250 cm (i.e. 50–200 kg) during the 1950s; then the size composition was solely comprised of fish >240 cm during the 1970s (>200 kg; see Fig. 3). Pusineri *et al.* (2002) showed that catch compositions dominated by older ages occurred during the same period in the main Spanish trap, suggesting that the East Atlantic and Mediterranean ABFT might have suffered poor recruitment years (perhaps driven by



**Figure 2** Catches of Atlantic bluefin tuna by the Nordic fisheries (i.e. Norway, Germany, Denmark and Sweden) between 1930 and 1990 (ICES and ICCAT data) and by the Japanese longline fisheries in the southwest Atlantic, offshore Brazil (ICCAT data).



**Figure 3** Size composition of the catches of the Norwegian fleet targeting bluefin tuna in the North Sea (data from ICES reports of the bluefin tuna working group from 1964 to 1981).

environmental changes and/or by overfishing). Alternatively, there may have been changes in migration patterns as suggested by Tiews (1978). A quick examination of data from the ABFT bait boat fishery in the Bay of Biscay (which only targets juvenile fish) does not indicate any recruitment failure during the 1960s. However, a more extensive analysis of the catch composition of the most important Atlantic and Mediterranean fisheries operating from the 1950s to the 1970s would be necessary to discriminate between these hypotheses.

Changes in migration patterns might also be the cause of the 'Brazilian episode'. This episode was a short period from 1962 to 1967 during which Japanese longliners caught 5000–12 000 tonnes of ABFT in an area where they usually caught tropical tuna (Fig. 2). Although the onset of the Brazilian episode coincides with the collapse of the Nordic fisheries, no clear link between the two has been established. Perhaps, the collapse of fishing in these two distant areas might have been due to overfishing on local (possibly isolated) populations of ABFT. However, in the case of the Brazilian episode, questions remain as to how a long-lived fish such as ABFT could have been fished out within 6 years by a few number of longliners.

#### Isolated populations or metapopulations?

Understanding the dynamics and spatial distribution of ABFT is crucial for management, as spatial variability governs the definition of management units, stocks and boundaries. The International

Commission for the Conservation of Atlantic Tunas (ICCAT) currently manages ABFT as two stocks with the boundary between the two spatial units being the 45°W meridian (Fig. 1). This delimitation was originally established for management convenience (for more details, see Stock Status and Management). But with the accumulation of observations from electronic tagging this management structure has been strongly criticized, as higher rates of trans-Atlantic migration than previously suspected have been detected (Lutcavage *et al.* 1999; Block *et al.* 2001). Based on an impressive and unique tagging effort (772 electronic tags being deployed), Block *et al.* (2005) advocated for the two ABFT populations hypothesis, each with its distinct spawning area (i.e. the Mediterranean Sea and the Gulf of Mexico), but with an overlapping distribution on North Atlantic feeding grounds. This hypothesis (which is certainly the best documented to date) implies that substantial changes in ICCAT management delimitations might be in order (see below Stock Status and Management). However, the major difficulty with electronic tagging relates to the representativeness of the sampled fish to the ABFT population as a whole. The last stock size estimate indicated that ABFT populations still include several million fish (ICCAT 2003b). Thus, even with the large number of electronic tags used to date, it is unclear if all the modes of ABFT behaviour are represented in the sample. Additionally, variability in trans-Atlantic migration rates inferred from conventional tagging studies appear to fluctuate greatly between years or decades (7.6% in the 1990s, 1.2% in 1980s, <1% in the 1970s and 2.3% in the 1960s, Fromentin 2002a). Therefore, obtaining a representative sample of electronic tagged fish may be out of reach at current costs. This makes the population migration rates still difficult to quantify from either traditional or electronic tagging (Porch *et al.* 2001).

Additionally, electronic tagging does not provide the location of birth of the migrating fish, a key information needed for understanding the population structure. To get this critical information, chemical signatures in hard structures of teleost fish (that represent natural tags) might help (Secor *et al.* 2002). Measuring the concentration of six elements (Li, Mg, Ca, Mn, Sr and Ba), Rooker *et al.* (2003) showed that the otolith chemistry of ages 0 and 1 – ABFT collected from the Mediterranean Sea and Gulf of Mexico nurseries could be distinguished (note that the three Mediterranean nursery

areas included in the study also displayed distinct differences). Using alternative geochemical markers (especially stable 18O isotope), Rooker and Secor (2004) could further discriminate otoliths chemistry from medium- and large-size ABFT. The presence of genetic stock structure in ABFT populations has also been investigated using microsatellite and mitochondrial DNA or isozymes (Broughton and Gold 1997; Pujolar and Pla 2000; Viñas *et al.* 2001, 2003; Ely *et al.* 2002; Carlsson *et al.* 2004). However, results are not yet conclusive and remain somewhat controversial. For example, Viñas *et al.* (2001, 2003) concluded that no genetic differences could be detected within Mediterranean ABFT, whereas Carlsson *et al.* (2004) reached the opposite conclusion. Such differences probably result from some discrepancies in the sampling design and/or markers used. Genetic and microchemistry analyses are undoubtedly very promising and should be extended, but in the case of ABFT population structure, genetic analyses need to be improved and standardized to avoid conflicting results.

Alternatively, one begins to question the concept of a stock itself, where populations are assumed to be both reproductively and geographically isolated. The traditional unit stock approach is related to discrete population concepts or the migrant/vagrant hypothesis (e.g. Sinclair and Iles 1989). However, another approach, based on the concept of 'density-dependent habitat selection' (MacCall 1990), might be more appropriate. Under the latter view, ABFT might be comprised of several groups of individuals which congregate at a certain spatial scale for reproduction, but whose population-level spatial range might expand and contract in response to both environmental and fishing variabilities (e.g. Smith and Jamieson 1986). However, neither of these two theories fully succeeds in explaining concomitant variability in migration patterns or the colonization and extinction of local populations in some areas vs. the strong persistence of specific spawning grounds and migration routes. Recent studies on salmon, herring and striped bass have opened new avenues for interpreting the complexity of fish dynamics that appear more appropriate. For example, concepts of imprinting and Clark's contingent definition purport that divergent energy allocations during early life stages can cause divergent migration or habitat uses among groups of fish (Clark 1968; Secor 1999). These differences could further persist in case of reproductive isolation, phenotypic plasticity and/or heterogeneous distri-

bution of the habitat. An alternative approach follows the concept of metapopulation theory from which ABFT would be seen as a collection of discrete local populations, occupying distinct and patchy suitable habitats, displaying their own dynamics but with a degree of demographic influence from other local populations through dispersal (Levins 1969; Hanski 1999; Kritzer and Sale 2004). Within each local population, individuals would display similar migration or habitat uses, resulting from a common spatial learning among individuals (Slatkin and Wade 1978; Olivieri *et al.* 1990; McQuinn 1997). Both hypotheses might provide a better explanation of the concomitance of homing behaviour with the occurrence of colonization and extinction in some areas. The main difference between Clark's contingent hypothesis and the metapopulation approach finally lies with the importance given to the deterministic (imprinting) vs. stochastic (behavioural) processes. More likely, there is no single factor but rather a mixture of mechanisms acting in ABFT populations. This issue is fascinating from an ecological viewpoint and crucial for management, as the effects of exploitation and the potential of the population to recover from overfishing depend on the ecological processes which are in effect.

## Biology

### Maturity

Earlier studies have found that *Thunnus thynnus* mature at approximately 4 years of age for the East Atlantic and Mediterranean Sea, but at around 8 years for the West Atlantic [length at maturity is about 110–120 cm (30–35 kg) vs. about 200 cm (150 kg) respectively; see Mather *et al.* 1995, for a review]. This disparity between the two sides of the North Atlantic has been used as a major argument for separation into two stocks. Related species such as the Pacific bluefin tuna (*Thunnus orientalis*) and southern bluefin tuna (*Thunnus maccoyii*) appear to mature as late as West ABFT (from 8 to 12 years depending on Caton 1991; Schaefer 2001). Comparing information on reproductive biology of tuna, Schaefer (2001) recently stressed the limited amount of information on size and/or age-at-maturity and the lack of valid histological criteria for this species. Subsequent to that investigation, new studies have been carried out in various areas of the Mediterranean Sea (ICCAT 2003c). Further progress has been

made in the determination of maturity by measuring hormone concentrations in blood (Susca *et al.* 2001). All these studies have confirmed past estimates, i.e. length at maturity at around 120 cm for female ABFT in the Mediterranean Sea. Differences in age-at-maturity between West Atlantic and Mediterranean ABFT might support the discrete population hypothesis (i.e. two stocks), but this remains rather puzzling given the apparent level of mixing. Further investigation is needed. A prerequisite would be to carry out extensive trans-Atlantic surveys to study maturity of ABFT using the same sampling protocol throughout the Atlantic and Mediterranean (see Perspectives).

### Reproduction

Bluefin tuna is oviparous and iteroparous like all tuna species (Schaefer 2001). It has asynchronous oocyte development and is a multiple batch spawner (spawning frequency being estimated at 1–2 days in the Mediterranean, Medina *et al.* 2002). Like most fish, egg production appears to be age (or size)-dependent: a 5 years old female produces an average of 5 million eggs (approximately 1 mm), while a 15–20 years female can carry up to 45 million eggs (Rodriguez-Roda 1967). Average fecundity was recently estimated from stereological quantification at around 93 oocytes  $g^{-1}$  of body mass for the East ABFT (Farley and Davis 1998; Schaefer 2001; Medina *et al.* 2002). The conventional assumption still is that adult ABFT spawn each year. However, electronic tagging experiments have shown that adult-sized fish have occurred some distance from any known spawning ground during the spawning season (Lutcavage *et al.* 1999). In addition, experiments in captivity (Lioka *et al.* 2000) raise questions about this assumption and suggest that spawning by an individual might occur only once every 2 or 3 years.

The location of spawning sites has been determined by noting either the location of fish with the appropriate gonadal condition or the distribution of larvae. Although both methods are subject to limitations (Schaefer 2001), it is generally agreed that ABFT spawning takes place in warm waters ( $>24$  °C) of specific and restricted locations (around the Balearic islands, Sicily and the Gulf of Mexico; Fig. 1) and occurs only once a year (around May and June for the West and East Atlantic respectively; Nishikawa *et al.* 1985; Mather *et al.* 1995; Schaefer

2001). In contrast to tropical tuna which spawn and feed throughout the tropical and subtropical oceans, ABFT appear to reproduce within a small spatial and temporal window (Fromentin and Fonteneau 2001). However, other spawning grounds, such as the Ibero-Moroccan embayment and the Black Sea, have also been mentioned in the past (Picinetti and Piccinetti Manfrin 1993; Mather *et al.* 1995). Picinetti and Piccinetti Manfrin (1993), who conducted egg and larvae surveys over the entire Mediterranean Sea between 1977 and 1988, concluded that spawning locations of ABFT were more distributed than usually accepted, extending into the Eastern Mediterranean Sea. A recent larval survey tends to confirm this (Karakulak *et al.* 2004). Electronic tagging experiments have further raised the possibility of ABFT spawning in the mid-Atlantic (Lutcavage *et al.* 1999). However, this has not been confirmed by recent larval surveys. Whatsoever, it appears that our understanding of ABFT spawning locations still remains incomplete.

ABFT appear to spawn when they reached specific locations (Rodriguez-Roda 1964, 1967), which has been supported by recent studies (Medina *et al.* 2002). These authors showed that very rapid gonadal maturity occurs between the time the migrating fish are caught in the Strait of Gibraltar and the fish spawn in the Balearic area a few weeks later. This rapid gonadal development is possibly influenced by increasing water temperature. Spawning fertilization occurs directly in the water column and hatching happens without parental care after an incubation period of 2 days. Fish larvae (around 3–4 mm) are typically pelagic with a yolk sac and a relatively undeveloped body form. The yolk sac is desorbed within few days, then the larvae have to feed on their own. The age-structure of the spawning stock and the condition of the spawners of ABFT may affect the reproductive potential and viability of offspring as has been shown for some groundfish and rockfish (Cardinale and Arrhenius 2000; Marteinsdottir and Begg 2002; Berkeley *et al.* 2004a,b; Bokko and Berkeley 2004). However, no specific information on ABFT is yet available. Fromentin and Fonteneau (2001) hypothesized that the small spatial and temporal window available for ABFT to reproduce (compared to tropical tunas) could increase temporal variability and, thus, result in higher risks of recruitment failure. But such an hypothesis presumes the existence of isolated population and would not be

pertinent to the case of metapopulations. Santiago (1998) suggested that the North Atlantic Oscillation (NAO) might affect ABFT recruitment success, but further investigations tend to dismiss such hypothesis (Fromentin 2002c; ICCAT 2002b; Ravier and Fromentin 2004). Thus, the identification of the major abiotic and biotic forces controlling ABFT recruitment remains elusive, primarily due to limited direct observation.

In summary the ABFT spawning strategy and subsequently the recruitment success is likely to be more complicated than the usually postulated homing behaviour to small and permanent reproductive areas of the Western Mediterranean and Gulf of Mexico. The degree of complexity of the ABFT population structure on the one hand and the potential impact of environmental changes on the spatial and temporal distribution of the spawning areas on the other (Ravier and Fromentin 2004) are likely to shape and modify the reproductive strategy of ABFT in both time and space.

### Feeding

Like many marine fish, ABFT larvae appear to feed primarily on small zooplankton, mainly copepods and copepoda nauplii (Uotani *et al.* 1990), whereas juvenile and adult ABFT are opportunistic feeders (as are most predators). Chase (2002) counted at least 21 species of teleost fish, two of elasmobranch fish and at least nine of invertebrates in the stomach samples of 568 ABFT and noted large differences among study areas, as well. The ABFT diet can include jellyfish and salps, as well as demersal and sessile species such as octopus, crabs and sponges (Chase 2002; V. Ortiz-Zarate, personal communication). But in general, juveniles feed on crustaceans, fish and cephalopods, while adults primarily feed on fish such as herring, anchovy, sand lance, sardine, sprat, bluefish and mackerel (Ortiz de Zarate and Cort 1986; Eggleston and Bochenek 1990; Chase 2002). Typically, ABFT stomach contents are dominated by one or two prey species, such as Atlantic herring and sand lance in the West Atlantic (Chase 2002) or anchovy in the East Atlantic and the Mediterranean (Ortiz de Zarate and Cort 1986). No clear relationship has been demonstrated between prey length and the size of ABFT: both small and large ABFT display similar prey-size spectra. However, Chase (2002) noted that the largest prey (those >40 cm) were only consumed by giant ABFT >230 cm. Usually it is postulated that

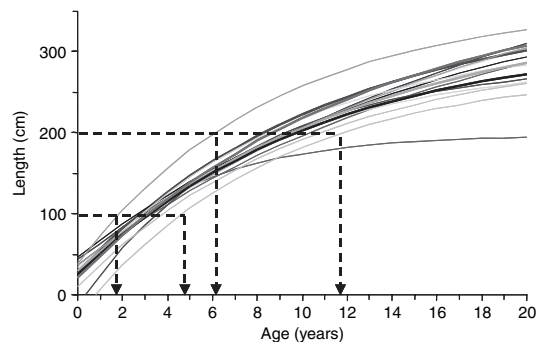
adults do not feed during the spawning season, but this supposition remains poorly documented and disagrees with observations made by one of us (JMF during aerial surveys) and reported by fishermen.

### Growth

Juvenile growth is rapid for a teleost fish (about  $30 \text{ cm year}^{-1}$ ), but somewhat slower than other tuna and billfish species (Fromentin and Fonteneau 2001). Fish born in June attain a length of about 30–40 cm long and a weight of about 1 kg by October. After one year, fish reach about 4 kg and 60 cm long (Mather *et al.* 1995). Growth in length tends to be lower for adults than juveniles, but growth in weight increases. Therefore, juveniles are relatively slim, whereas adults are thicker and larger. At 10 years, an ABFT is about 200 cm and 150 kg and reaches about 300 cm and 400 kg at 20 years (of course there is considerable variability between individuals). Maximum sizes (and probably age) appear to be much larger, as fish from 625 to 685 kg have been reported in Italian trap catches (Sara 1969) and an individual of 427 cm and 726 kg has been caught in the Gulf of Maine (Bigelow and Schroeder 1953). Purportedly, West ABFT grow faster after maturity and attain larger sizes than the East and Mediterranean ABFT (ICCAT 1997). A few studies also suggest that males grow faster than females and are proportionally more frequent in catches of individuals larger than 250 cm (Mather *et al.* 1995). Seasonal growth patterns have been better documented. Seasonal patterns have also been noted for the southern bluefin tuna (Evenson *et al.* 2004). Both juvenile and adult ABFT grow rapidly during summer and early autumn (up to 10% per month), while growth is negligible in winter (Tiews 1957; Mather *et al.* 1995; Labelle *et al.* 1997). Additionally, Fromentin (2003) described significant year-to-year and decadal variations in weight-at-age of juveniles in the Western Mediterranean Sea, which could be related to environmental changes and/or age or size selection patterns of fishing.

The ageing procedure used for ABFT has variously been based on the count of marks on hard structures, length-frequency data or mark-recapture data. Still, age–size relationships remain uncertain, especially for older individuals  $>8$  years. The count of annuli on otoliths, spines, vertebrae and scales is impaired by various sources of errors due to factors such as the coalescence or the disappearance

of the first marks or conversely to the multiple marking due to migration patterns (Compean-Jimenez and Bard 1980, 1983; Farrugio 1981; Cort 1991; Mather *et al.* 1995). Decomposition of ABFT length-frequency data into age classes (e.g. Bhattacharya 1967) becomes difficult for fish older than 5 years, as the cohorts tend to become indistinguishable. In addition, intensive fishing on juveniles tends to smooth over modal differences that might have originally existed. Mark-recapture-based growth curves used for ageing do not perform well for fish  $>200 \text{ cm}$  (approximately 10 years old), either. This is due to the scarcity of observations and high variability in growth for these sizes (Turner *et al.* 1991). Consequently, there is considerable variation between the von Bertalanffy equations estimated by various authors (Fig. 4). The age estimate for a fish of 1 and 2 m in length ranges over 3 and 6 years respectively. The application of more advanced technologies such as electronic microscopes used to investigate the annuli on hard structures or electronic tagging to get precise spatial and temporal information may help in distinguishing between observation error (error resulting from sample size, count of marks on hard structures, etc.) and process error (resulting from natural spatial and temporal variation in growth). Innovative modelling approaches such as the growth model developed by Evenson *et al.* (2004) which integrates data from the three key sources (length-frequency, tag-recapture and hard structures) within the same estimation framework could and should be applied to ABFT.



**Figure 4** Corresponding curves of the 16 Von Bertalanffy equations published by various authors since Sella (1929) for the Atlantic bluefin tuna (the 2 curves currently used by the SCRS for the East and West stock assessments are highlighted by thicker lines).

Fromentin and Fonteneau (2001) showed a clear contrast between life history traits of tropical tuna and ABFT. The former are characterized by a rapid growth, an early age-at-maturity, continuous spawning, a limited maximum size, a short life span and a distribution restricted to warm waters, whereas ABFT typically display opposite characteristics similar to cold-water species: slower growth, later maturity, shorter spawning season, larger size and longer life span. These life history traits make ABFT more vulnerable to exploitation than tropical tuna (Longhurst 1998; Fromentin and Fonteneau 2001).

### Natural mortality

Like many fish populations, natural mortality rates of ABFT (denoted by the instantaneous annual rate,  $M$ ) are poorly known. However, it is generally agreed that: (i) long-lived fish, such as ABFT, have a lower and less variable  $M$  than short-lived ones; (ii)  $M$ s are higher during juvenile stages than during the onset of adulthood (disregarding senescence); and (iii)  $M$ s also vary with population density, size, sex, predation and environment (for a review on  $M$ , see e.g. Vetter 1987). As ABFT is a highly migratory and pelagic species, competition and cannibalism due to food and/or habitat limitations are expected to be lower than for groundfish (Myers and Cadigan 1993; Fromentin *et al.* 2001). Predation purportedly comes mainly from large pelagic sharks and killer whales. Historical observations (as noted in the archives of the Dukedom of Medina Sidonia) and recent studies (Nortarbartolo di Sciarra 1987) indicate the occurrence of killer whales at the entrance of the Gibraltar Strait during the ABFT spawning migration. In addition, it appears that the proportion of males is higher in catch samples of large individuals, which might indicate a higher  $M$  or lower growth for females ABFT (ICCAT 1997). However, differences in the sex ratio do not appear as strong as those for billfish or swordfish (Arocha and Lee 1996). Tagging from southern bluefin tuna (*Thunnus maccoyii*) tends to confirm that  $M$  is higher for juveniles (between 0.49 and 0.24) compared to that of adults (around 0.1). These rates are also relatively low in comparison to tropical tuna (ICCAT 1997; Hampton 2000). In the absence of direct and consistent estimates of  $M$  for ABFT, the natural mortality vector of the southern bluefin tuna is generally used for the East Atlantic and

Mediterranean ABFT stock assessment, whereas a constant  $M$  of 0.14 is assumed for the West Atlantic ABFT (ICCAT 1999). However, both solutions remain unsatisfactory and tagging experiments and modelling are needed to progress on this issue (see Perspectives).

### Fisheries history

#### From ancient times to the 19th century

Archaeological excavations have shown that fishing on ABFT has occurred in the Mediterranean since the 7th millennium BC (Desse and Desse-Berset 1994). About a 100 separate fisheries targeting tuna, bonito and sardine were established (along with salting plants) by the Phoenicians, then by the Romans around the Western Mediterranean Sea (Doumenge 2000). Ancient Greek or Roman poets and philosophers, such as Aristotle, Pliny the Elder, Oppian and Aelian, gave extensive descriptions of fisheries exploiting ABFT migrating into the Mediterranean for spawning (see also Farrugio 1981; Mather *et al.* 1995; Doumenge 1998). At that time, fishermen primarily used hand lines and several varieties of seines, particularly beach seines. Between the 16th and 19th centuries, beach seines were progressively replaced by traps (Doumenge 1998; Ravier and Fromentin 2001). Traps and beach seines were used throughout the Mediterranean and Gibraltar strait and were the first industrial fisheries in this area. These fisheries comprised an important use of labour for fishing and canning (Fig. 5) and substantial capital investment from Italian (mostly Genovese) bankers (Pavesi 1889; Berthelot 1988; Doumenge 2000).

The European scientific programme STROMBOLI collated historical information from national and private archives, scientific libraries and various Mediterranean laboratories, then reconstructed and analysed more than 100 time series of bluefin tuna trap catches since the 16th century (Fromentin 2002b). The mean range of the annual trap yields was estimated to have been about 15 000 tonnes year<sup>-1</sup>, but with large fluctuations. However, annual yields did not seem to exceed 30 000 tonnes and were rarely below 7000 tonnes (Ravier and Fromentin 2002). These estimates confirmed the intensity of exploitation of ABFT by the ancient trap fisheries cited previously by historians.

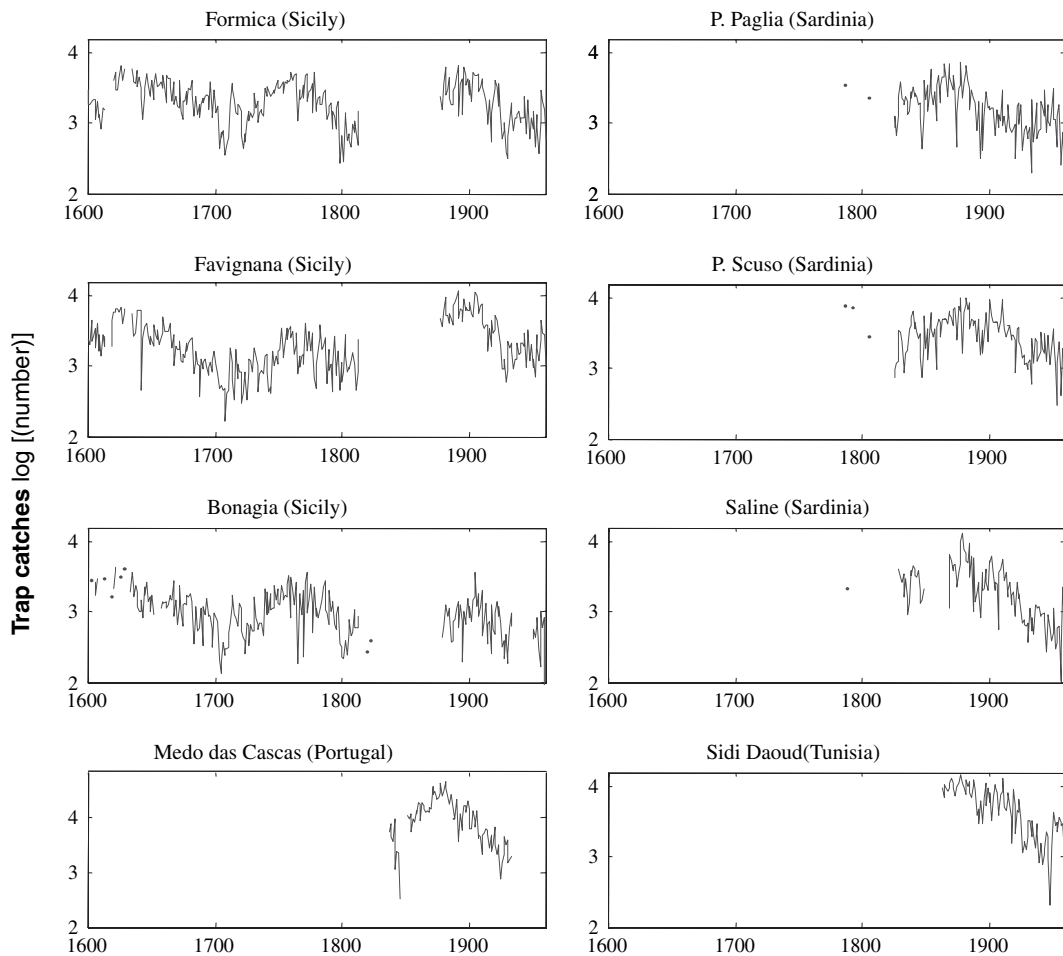


**Figure 5** Picture of traditional tuna fisheries during the 17th century close to Cadiz (South of Spain, from G. Braun and F. Hogenberg, 1612 - *Civitates Orbis Terrarum*, Colonia). In this area, migrating bluefin tuna through the Gibraltar straight were detected by guards standing at the top of the towers. Fish were caught by large beach seines and directly canned in local manufactories. Beach seines implied a greater amount of workforce than traps (the latter replacing the former in the western Mediterranean since the 16th century and along the Spanish coast during the early 19th century). Most of these fisheries constituted important establishments with a real economic stack and bankers were often involved in these fisheries.

A striking result was the finding of a dominant 100–120 years periodic fluctuation in the trap catches (Fig. 6; Ravier and Fromentin 2001). As these long-term fluctuations were synchronous between areas of the Western Mediterranean and near North Atlantic (over a distance of some to 2500 km), the authors postulated that this pseudocycle reflected variations in the abundance of ABFT entering the Mediterranean each year for spawning. In a subsequent analysis, Ravier and Fromentin (2004) showed that these long-term variations in trap catches were inversely related to temperature and could, therefore, result from changes in migration patterns of ABFT spawners in response to modifications in oceanographic conditions.

### The 20th century

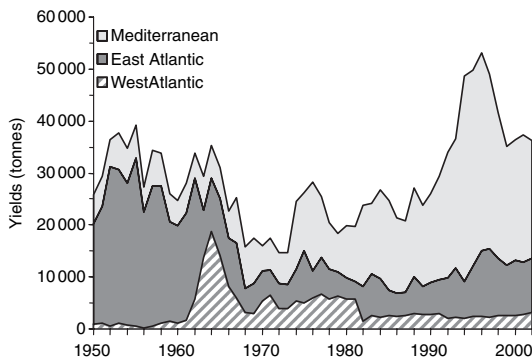
Traps underwent few technical modifications until the early 20th century, but increasing coastal traffic, noise, and coastal pollution may have contributed to a reduction of the trap efficiency at the beginning of the 20th century (Addis *et al.* 1997; Ravier and Fromentin 2001). Until that period, ABFT fishing primarily occurred in the Mediterranean Sea and the Ibero-Moroccan embayment, but exploitation progressively expanded during the 19th century. A hand line fishery targeting juvenile ABFT and North Atlantic albacore (*Thunnus alalunga*) arose in the Bay of Biscay during the mid-19th century (this fishery, which is nowadays mainly composed of bait boats, is still in activity, see



**Figure 6** Plots of long time series (between 80 and 360 years long) of Atlantic bluefin tuna catches from 8 traps between 1599 and 1960 (catches are expressed in the log-number of fish caught over a given year, for more details see Ravier and Fromentin 2001; 2004). The 8 traps were set along the West coast of Sicily, North and South coasts of Sardinia, South coast of Portugal and North coast of Tunisia. A few traps are still set nowadays.

Bard 1981). ABFT was also occasionally caught in the North Sea, Norwegian Sea and Kattegat since the 1930s by a new active gear, the purse seine (Meyer-Waarden 1959). These Nordic fleets grew rapidly such that their production exceeded that of the traditional trap fisheries during the 1950s, catching up to 16 000 tonnes year<sup>-1</sup> (Figs 2 and 7). Their catches were mainly composed of large ABFT migrating North in summer to feed on pelagic fish, such as herring and sprat (Hamre *et al.* 1968; Pusineri *et al.* 2002). The Norwegian fleet, which was the most important of the Nordic fleets (about 80% of the total Nordic catch), was the only one remaining active after the sudden collapse in 1963 (possibly due to changes in migration patterns, see Ecology and Population Structure).

During the same period, fisheries also emerged along the edge of the western Atlantic continental shelf, especially between Cape Hatteras and Newfoundland (Mather *et al.* 1995). Fisheries for juveniles were conducted by purse seines extending northward to Cape Cod and Maine in the 1950s and 1960s (Fig. 8). Rod and reel sportfishing catches of juveniles were also important in some years. At that time purse seining of juveniles was the dominant portion of the catch. Additionally, small fisheries for large fish were conducted by hand lines, traps, harpoons and rod and reel. However, markets for large fish were not fully developed and demand for these fish was low. Longlining in oceanic waters of the western Atlantic also developed in the 1960s, primarily by Japan (Fig. 8). The longliners focused



**Figure 7** Official total catches of Atlantic bluefin tuna between 1950 and 2003 reported to ICES and, then to ICCAT. Total catches are split in the three main geographical areas, i.e. the Mediterranean Sea, the East and West Atlantic. Catches mainly occurred in the northeast Atlantic (North Sea and Norwegian Sea) during the 1950s, in the West Atlantic during the mid-1960s (offshore northern Brazil) and in the Mediterranean since the 1970s.

primarily on medium-sized fish, but concentrations of large fish were exploited if encountered (such as the Brazilian episode between 1962 and 1967 mentioned in Migration and Stock Delimitation; Figs 2 and 7). During the 1970s, these fisheries moved to the Gulf of Mexico (the only known spawning area of the western Atlantic) to target large fish (Fig. 8).

The late 1960s and early 1970s were a transitory period for both the Atlantic and Mediterranean ABFT fisheries. The landings were lower than in the previous decades (approximately 12 000 tonnes year<sup>-1</sup>; Fig. 7), because of the decreasing activity of the traps and Nordic fleets in the East Atlantic and a reduction in purse seine catches of juveniles in the early 1970s in the West Atlantic (attributable to recruitment declines). Also during that period, purse seine and longline fleets progressively replaced the traditional fisheries of the Mediterranean and East Atlantic.

The development of the Japanese sushi-sashimi market during the 1980s was the most remarkable event of recent decades, as it made ABFT exploitation much more profitable than before (Fromentin and Ravier 2005; Porch 2005). Consequently, there was a sharp increase in the efficiency and capacity of the established fisheries during the 1980s and 1990s. For instance, a standard French purse seiner in 1998 was twice as long and four times more powerful than it was in 1970 (engines were 170

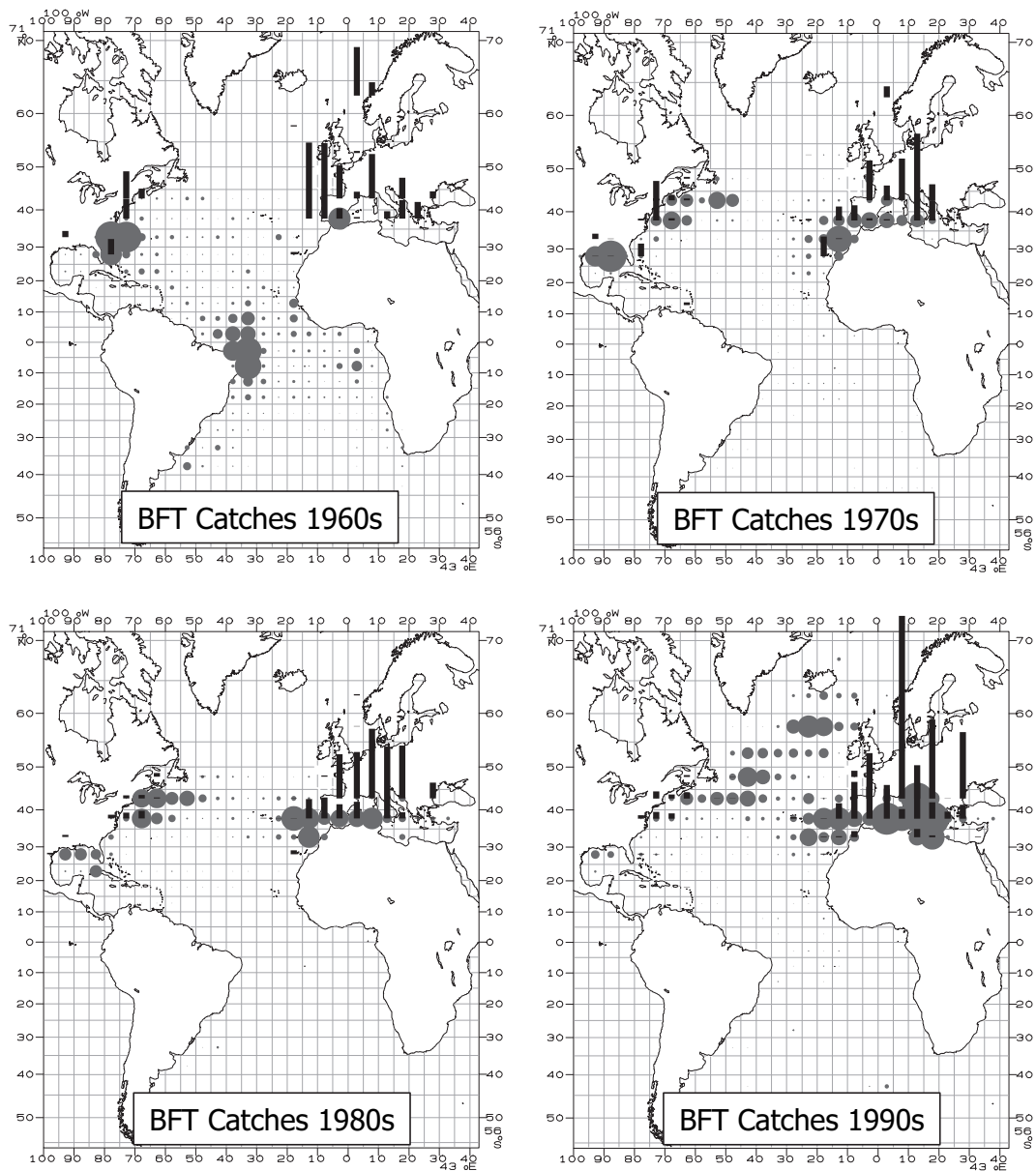
and >800 W in 1970 and 1998 respectively) and further included powerful positioning and searching equipment, such as bird radars, sounders, sonars and planes (Liorzou 2001). Furthermore, new storage technologies (such as carrier vessels with deep-freezing storage) and caging systems (for holding and fattening fish) were recently introduced and greatly modified both fishing strategies and efficiency (for a recent detailed report on the ABFT caging system, see Bregazzi 2004). These profitable conditions (the value of a fish put into cage is about double that of a frozen fish of high quality) also induced a rapid development of new and powerful fleets, especially in the Mediterranean countries.

Consequently, the fishing areas economically available for exploitation expanded in both the North Atlantic and Mediterranean (Fig. 8). The Mediterranean Sea is a typical example of this. While traditional ABFT fisheries mostly operated along some coasts until the mid-1980s (e.g. the Gulf of Lions, the Ligurian, Ionian and Adriatic Seas), the fisheries rapidly expanded over the whole Western basin during the late 1980s and early 1990s. Most recently the fisheries have expanded over the Central and Eastern basins such that ABFT is now exploited over the whole Mediterranean Sea (including offshore areas) for the first time in its long millennial fisheries history. The expansion of the Japanese longline fleets in the Central North Atlantic mostly along the Gulf Stream during the 1990s (Fig. 8) was equally as striking. The redistribution of the fisheries resulted in rapid increases in yields since the 1980s, especially in the Mediterranean Sea. The Mediterranean has now regained its dominance as the most important fishing ground (Fig. 7). Catches in the East Atlantic and Mediterranean reached an historical peak exceeding 50 000 tonnes during the mid-1990s. Subsequent reductions in the magnitude of landings are questionable, as under-reporting may have occurred after the implementation of a total allowance catch (TAC). Catches are likely to have remained at around 40 000–50 000 tonnes for a decade (Fromentin 2003; ICCAT 2005). During the same period, a strict catch quota at around 2500 tonnes was implemented in the West Atlantic.

## Stock status and management

### Background

ABFT is managed under the auspices of the ICCAT, a convention of signatory member nations where



**Figure 8** Total catches of ABFT per decades (1960–1969; 1970–1979; 1980–1989 and 1990–1999), per geographical locations (5 × 5 square) and per main gear: bars represent the total catches of surface gears (i.e., mostly purse seine, but also bait boat, hand line and trap); circles represent the total catches of long line.

the stated goal is the maximum sustainable catch of tuna and tuna-like species (ICCAT 2003a). Member nations annually provide catch and effort statistics from their tuna fisheries and results of relevant biological and ecological research to the Secretariat of ICCAT. These data form the basis for developing scientific advice. Stock-assessment analyses are performed by ICCAT's Standing Committee on Research and Statistics (SCRS) composed of national

scientists from the member states. The Commission, itself, uses the scientific advice in negotiating binding agreements between member nations (the implementation is left to the authority of the member countries, for more details see <http://www.iccat.int>).

Since the Commission's inception in the early 1970s, ICCAT and the SCRS have been concerned with the status of ABFT (the first ICCAT recom-

mendment was made in 1974 to limit effort and size limit on ABFT). However, comprehensive stock assessments of the resource began to be used in the late 1970s through the introduction of cohort analysis and virtual population analysis (VPA), i.e. untuned VPAs. Cohort analyses as they were constructed at that time required that catch, catch-at-age and natural mortality rates were known for the entire life-span of a cohort and that the population was closed. In the case of ABFT (as other species), each of the basic assumptions of the analytical methods have been questioned. Subsequently, auxiliary data [primarily catch-per-unit-effort (CPUE) indices of abundance] began to be included in the analyses to estimate trends of abundance in the most recent years of the analysis. The approach used to compare VPA-derived abundance trends with CPUEs has gradually become more rigorous, progressing from maximization of correlation to least squares minimization and to, more recently, with the maximum likelihood estimation.

With the advent of more integrated methods of estimating status which utilized auxiliary information through tuning of ADAPT-VPAs, the debate shifted to the CPUEs (i.e. the appropriateness of their use as indices of abundance or to the weighting of disparate indices representing different portions of the population) and to the magnitude of error in the catch and catch-at-age (which are assumed theoretically to be null, see, e.g. Cotter *et al.* 2004). However, in many cases sampling has been sparse, especially in the 1960s and even in more recent years in the Mediterranean (see below). More statistically based models (Fournier *et al.* 1998) in which error structures of catch-at-age and other inputs are explicitly modelled, have been also explored (Porch and Turner 1997). While these methods have exposed some inconsistencies in the signals from catch-at-age data, tagging data and the CPUEs, no clear-cut solution to weighting these data presently exists for either these methods or more traditional ADAPT-VPAs.

However, the longest debate has centred on population structure and stock identification. In 1971, a one-stock hypothesis was deemed more plausible for the Atlantic with some separation between Atlantic and the Mediterranean components of the populations. In 1976, the SCRS considered factors which supported a two-stock hypothesis (two stocks being the western Atlantic vs. the eastern Atlantic and Mediterranean com-

bined) and those supporting one stock. The factors supporting two stocks included the occurrence of small-to-large fish on both sides of the ocean, the occurrence of spawning on both sides, no evidence of spawning activities in the mid-Atlantic, tagging and historical records of traps in the Gibraltar area that show ABFT entering into the Mediterranean spawning area, the distribution of larvae and juveniles in the Mediterranean and irregularities of trans-Atlantic tag returns (for a recent review, see ICCAT 2002a). On the contrary, factors supporting a one-stock hypothesis were similar in growth rates and the occurrence of trans-Atlantic tag returns. In 1980, the SCRS presented stock assessments separately for east and west stocks, and for a total Atlantic stock. The area divisions were suggested for statistical convenience and because they were aligned with discontinuities in the distribution of catches *at that time* in the Atlantic. The division line (i.e. 45°W) adopted at the 1980 SCRS session was used to define the East and West stock management units. In 1981, the Commission set a 'scientific monitoring level' for the West stock. Effectively, the scientific monitoring level was simply a TAC that was negotiated within the Commission. The goal was to set the level low enough to initiate recovery. The Commission continued to refer to this level as a scientific monitoring quota for some years, whereas the scientists simply referred to it as a TAC.

However, recent events in the fishery coupled with new scientific evidence suggest that the simple East–West management boundary may no longer be the most appropriate mechanism for management. Electronic tagging indeed demonstrated that substantial movement of large ABFT from West to East occurred, but that the migration routes were complex (Block *et al.* 2001; Lutcavage *et al.* 2001). It was also showed that even small rates of net movement across the East–West boundary could have significant implications on assessment and projections (i.e. on future catch levels, Punt and Butterworth 1995). Just as significantly, ABFT fisheries moved and expanded. Originally, they tended to be located relatively close to the continents, but the central Atlantic region has become an important fishing ground since the 1990s (Fig. 8). Consequently, the overall distribution of catch appears more continuous across the North Atlantic than was seen in previous decades (ICCAT 2002a). In response to the changing circumstances, research was conducted on alternative assessment methods which incorporate movement (e.g. Punt

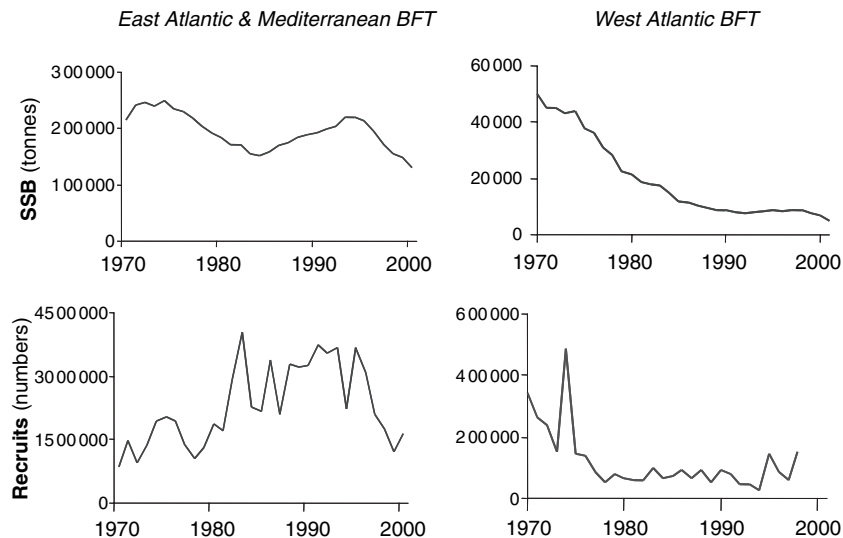
and Butterworth 1995; Turner and Powers 1995; Cooke and Lankester 1996; Porch and Turner 1999). In particular movement and mixing models focused on diffusion (where the probability of trans-Atlantic migration depends only on the location of the potential migrant) and overlap (where the ranges of the eastern and western populations are assumed merely to overlap). While understanding the characteristics of ABFT mixing through the development of a 'true' model of movement is important, perhaps, a more important goal is to develop movement models that are useful for management purposes. For instance, Powers and Cramer (1996) suggested that incorporating reproductive behaviour of the stock into models is important, if the objective is to maintain a viable western spawning population, whereas it is less so if the objective is to maintain high yield ocean-wide. In response to this assessment research, the SCRS has begun to focus on appropriate management models, rather than defining a 'correct' movement model or a single-stock identification hypothesis (ICCAT 2002a).

#### Current status

Currently, stock assessments continue to be conducted using VPAs separately for the western Atlantic vs. the eastern Atlantic plus Mediterranean

(ICCAT 2003b). While the weaknesses associated with these assessments are known (see above), the analyses still provide a basis for management, because: (i) consistent techniques are needed to monitor the recovery plan for the West component; (ii) simulation studies suggested that more biases may be introduced into the assessment if mixing is inappropriately incorporated into the assessment models; (iii) the much larger magnitude of abundance of the East Atlantic and Mediterranean ABFT compared to this of the West Atlantic ABFT meant that the dynamics of the West component had little influence on the East one (whereas, the converse is not true); and (iv) the basic data deficiencies in the Mediterranean Sea made it difficult to reliably model the two components simultaneously. Nevertheless, ABFT assessments still explore mixing scenarios as sensitivity analyses.

Catches of the West component have not varied very much since 1982 due to the imposition of management quotas (the range over this period is 2100–3000 tonnes; Fig. 7). Additionally, the estimated spawning stock size (SSB) and recruits have been relatively stable since the mid-1980s (most of the declines occurring during the 1970s; Fig. 9). However, the potential productivity of the stock, future recruitment levels and the consequences of future catches on SSB trends remain uncertain and still lead to intensive debates.



**Figure 9** Results of the retrospective analyses for the East Atlantic and Mediterranean stock (left panel) and West Atlantic stock (right panel) from the 2002 SCRS bluefin tuna stock assessment (ICCAT 2003b). Spawning stock biomass (top graphs) and recruitment (bottom graphs) are given for the base cases. Note the differences in scaling between both stock (estimates from the East stock being 5 to 10 times higher than these of the West).

Additionally, there are great uncertainties about the total catches and their size composition for many fisheries of the East Atlantic and Mediterranean ABFT since the late 1990s (ICCAT 2005). This together with the unknown adequacy of available CPUE indices as measures of overall stock abundance, make it difficult to interpret trends in SSB and recruits estimated from the VPA (Fig. 9). For instance, the apparent regime shift in the recruitment during the early 1980s is likely to reflect the important changes in the selectivity pattern of the purse seiners. These fleets used to primarily catch juveniles ABFT, but they now target large fish during the spawning season in response to demand of the sushi-sashimi market. Consequently, the catch-at-size matrix of the East Atlantic and Mediterranean ABFT includes a much higher proportion of catches of large fish since the mid-1980s. In the absence of corresponding auxiliary information, the VPA naturally translates this change into a higher recruitment level since the early 1980s. However, it is unlikely that this higher level did, indeed, occur. Because of this uncertainty, the stock recruitment relationship was not an integral part of formulating the management advice. The productivity of the East stock has been estimated through different methods at around 25 000 tonnes (ICCAT 1997, 1999, 2003b). Despite potential biases due to various model assumptions and data quality, the recent estimates of productivity done by the SCRS are consistent with past studies (e.g. see Farrugio 1981).

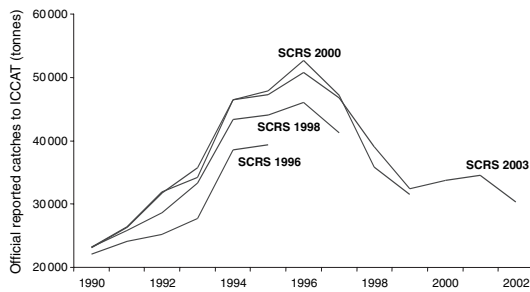
### Current management

International conservation groups became more interested in the status of ABFT as the abundance of the resource declined particularly for the western component. Indeed, there was some impetus for the listing of ABFT under the Convention on International Trade in Endangered Species of Wild Flora and Fauna in the early 1990s. This did not come to pass. However, the debate raised the issue of monitoring of the trade in ABFT. In response, ICCAT developed a 'statistical document', i.e. a regulatory mechanism to require documentation of the trade of ABFT as it travels to the market primarily in Japan. The statistical document reduced the amount of unreported catches. Additionally, data derived from the documents provided scientists with a mechanism to make initial estimates of the unreported catches (ICCAT 2003c).

In 1998, ICCAT further adopted a rebuilding programme for the West Atlantic in which the biomass of adults at maximum sustainable yield is to be attained by 2018 with a 50% or greater probability. The programme states that the TAC for this component should be at 2500 tonnes ( $\pm 200$  tonnes depending on future SCRS advice). For the East Atlantic and Mediterranean ABFT, the Commission recommended in 2002 that ABFT catches should not exceed 32 000 tonnes for the period 2002–2006 (since its implementation in 1998, the TAC varied between 29 500 and 32 000 tonnes).

Additionally, an Atlantic-wide size limit of 6.4 kg (i.e. age 2) has been in force since 1975. This was recently raised to 10 and 30 kg for the Mediterranean Sea and West Atlantic respectively. The discrepancy between the minimum sizes between the sides of the ocean occurs because of the disparity in age-at-maturity between the West and East ABFT (see above) and, as well as to differences in the fisheries. The West fisheries include an important recreational fishery (partly on juveniles) which has adapted to catch and release programmes. Furthermore, commercial fishing in the West Atlantic mostly target large fish, whereas traditional fisheries in the East Atlantic and Mediterranean Sea still target small juveniles fish (see above). Size limit regulations in the East and Mediterranean may be more accepted by fishermen nowadays than they were in the past, as recent observers on board programmes tend to show (Fromentin and Farrugio 2005). However, the situation probably varies among fleets and areas. Substantial amounts of under-size fish are still suspected to be caught in the East Atlantic and Mediterranean Sea because traditional and artisanal fisheries still target juveniles ABFT. However, the numerous landing locations make comprehensive control difficult. During the 1990s, the prohibition of longliners, purse seiners and aerial spotting planes has been imposed in the Mediterranean Sea during given periods of the year (ICCAT 2004).

In the East Atlantic and Mediterranean ABFT, these management regulations are believed not to have been very effective in limiting catches, especially in the Mediterranean Sea where significant misreporting has been suspected (Fig. 10, see also Fromentin and Ravier 2005; ICCAT 2005). The implementation of the TAC has induced incentives which cause perverse results for data collection (Fromentin 2003). The TAC regulation implies that



**Figure 10** Comparison of Task I nominal catches for the East Atlantic and Mediterranean bluefin tuna stock, as reported to ICCAT secretariat in 1996, 1998, 2000, and 2003. Differences between series mainly come from a major revision of the catch made by various fishing entities in 1998, i.e. after the implementation the TAC on the East stock. These revisions concern the 1990–1996 period and are likely to reflect over-reporting, as the quota of each entity is proportional to its historical catches. Differences between the 1996 and 2000 Task I series can exceed 20% in some years.

the same information, i.e. the landings, is used to: (i) evaluate the state of the stock; (ii) manage and control the whole fishing activity; and (iii) allocate quotas between contracting parties. The procedure, thus, describes a circle where the components of the system are tightly linked to one another. In an environment of over-capacity and high economic interests, it is difficult to completely avoid misreporting and fraud and, thus, the assessment-management system may be caught in a vicious circle. This is especially true when the stock is shared by many entities having divergent interests. Note that inefficiencies of TAC systems have also been questioned for some groundfish stocks (Cotter *et al.* 2004). Nevertheless, TAC systems can be and have been successful, especially when management regulations are adequately enforced and associated with appropriate incentives (Hilborn *et al.* 2004).

During a review of the fisheries data available for the East Atlantic and Mediterranean ABFT, ICCAT (2005) identified problems other than potential under-reporting: (i) the presence of many data sets which are unclassified as to gear or are aggregated over gears, areas and seasons and (ii) the lack of size composition of the catches for several major purse seine fleets (that represent more than 50% of the total Mediterranean yields). This problem has been mostly due to the development of caging and farming operations where fish are held in cages and fed and are not immediately landed. Thus,

captured fish and the data associated with their size at capture were not normally accessible to scientists. The proportion of the catches which have been sampled for sizes and reported to ICCAT always fluctuated, but it dropped below 5% in the Mediterranean Sea since 1998. Consequently, many substitutions (data pooling strategies) have to be used to reconstruct the final catch-at-size and catch-at-age matrices. The SCRS, thus, concluded that it was no longer defensible to assess the East Atlantic and Mediterranean population using methods that assume that the catch-at-size (age) is known exactly, until extensive improvements in fisheries statistics are made. In the interim the efficacy of 'more robust' methods involving simple management procedures should be explored (ICCAT 2005). Note that the harmful effects of tuna farming on catch statistics, fishing pressure on small pelagic fish and introduction of viral diseases were also stressed by conservation organizations for several years (e.g. WWF 2002, 2005).

For the West, there is a concern that the level of mixing across management unit boundaries might adversely affect the recovery in the West Atlantic. Essentially, increases in biomass of western fish may be moving across the border and being captured by eastern fisheries before they fully contribute to western recovery (ICCAT 2002a; Porch 2005). This concern has increased together with the growing intensity of exploitation in the East Atlantic and Mediterranean Sea and the accumulation of evidences of trans-Atlantic migrations from electronic tagging. Therefore, ICCAT (2002a) suggested several management and modelling approaches to address these spatial problems. Most promising is the development of operating models, i.e. models integrating biological realism with robust management procedures (Powers and Porch 2004, Kell *et al.* 2003). These approaches allow contrasting and competitive biological and ecological hypotheses to be tested for their utility and robustness against various management scenarios. These could greatly help assessment and management of various kinds of situations, including data poor situations.

## Perspectives

### Status and futures of the stocks

Large uncertainties in the basic fisheries statistics for the East Atlantic and Mediterranean ABFT

together with the lack of knowledge on key processes in the population dynamics (reproduction, migration and population structure) have strongly influenced and, possibly, biased the perception of the status of both the East and West stocks. For instance, the evaluations done in the 1970s and early 1980s underestimated ABFT productivity. Thus, it might be tempting to argue that these large uncertainties allow for postponement of the implementation and control of more ambitious management measures, justifying the status quo. Nevertheless, despite the current uncertainties, we do believe that ABFT as a whole has been undergoing heavy overfishing for a decade. Indeed, the intensity of the current exploitation is the highest in the long history of ABFT fisheries in the Mediterranean Sea (Fromentin 2003; ICCAT 2003c). The current capacity of the purse seine fleet (more than 200 units in the Mediterranean Sea) and longline fleet together exceed the mean productivity of ABFT (estimated at approximately 25 000 and 2500 tonnes for East and the West stock respectively; ICCAT 1999, 2003b). Furthermore, the historical perspective given by the centuries-old trap fisheries and the Nordic fisheries indicates that current yields in the East Atlantic and Mediterranean Sea are more than two times higher than historical records and mean estimated productivity as well (see above). Lastly, the spatial expansion of the fisheries has considerably reduced the area where ABFT is *not* exploited; this is a spatial expansion that is directly related to the sharp increase of the fishing pressure and fishing efficiencies during the two last decades rather than to a change in ABFT spatial distribution.

ABFT fisheries in the Mediterranean provide an illustration of a rendition of the 'race-for-fish' strategy described by Hilborn *et al.* (2003). Normally, the race-for-fish is conducted by competing fishers to get the most fish prior to the TAC be reached. In this case the race is to capture as much market and infrastructure as possible before the TAC is meaningfully implemented. It remains unclear to what extent improvements in TAC implementation for the East Atlantic and Mediterranean ABFT has slowed this process. This situation, coupled with the life history characteristics of ABFT, very high value and relatively poor monitoring suggest that the exploitation of ABFT has many biological and economic traits that have led several fish stocks to depletion in the past (Hilborn *et al.* 2003). The challenge is now as much (and

maybe more) organizational and institutional as it is scientific. While from a scientific viewpoint the priority is to obtain adequate and reliable fisheries statistics, the future of ABFT might also involve important modifications to access and governance structures (Hilborn *et al.* 2005).

### Research priorities

Improvements in scientific research are thus necessary but not sufficient conditions for improvements in long-term management. However, better understanding of key ecological processes is also needed, especially on the habitat and the spatial dynamics of this highly migratory species. The success with which we take up this challenge will depend on our ability to collect novel fishery-independent observations. Such a novel method to do this is through the use of archival tags and their associated 'biologgers'. While there is no doubt that bio-logging technologies have produced impressive results during the last decade (e.g. see Gunn and Block 2001), their technical development and scientific utilization still has considerable limitations: (i) electronic tags have been developed for use with different species and for different research goals and are built and commercialized in small numbers. Consequently, they often remain too expensive for large-scale experiments (approximately 4000 € per pop-up archival tag); (ii) geolocation in archival tags is deduced from light information and is, thus, impaired by relatively large errors of about one to three degrees in average (i.e. 60–180 nautical miles); this magnitude of error is inconsequential for broad-based location studies, but the same magnitude of error becomes excessive when correlating movements with fine-scale oceanographic events (Sibert *et al.* 2003; Teo *et al.* 2004; Royer *et al.* 2005); (iii) tag attachment needs to be improved to avoid numerous premature jettisons; (iv) satellite transmission of pop-up tags can fail for various reasons such as lack of satellite coverage in the area of the pop-up and bad weather conditions; (v) current archival pop-up tags can still only be implemented on large fish; and (vi) the resulting data have not been fully exploited, as the ecological or oceanographic context is not easily accessible to biologists. Therefore, technical improvements are still needed to create effective, reliable, widely usable bio-logging devices, and to integrate a framework to acquire, process, store and visualize tag data coupled with the ocean descriptions now operationally

available from remote sensing and numerical ocean models.

As we believe that the spatial dynamics of ABFT is central to understanding the population dynamics of this species, electronic tagging is expected to be an important tool. Nonetheless, electronic studies alone will not be sufficient to get a comprehensive picture of ABFT population dynamics. It is also critical to discriminate between putative spawning sites and nurseries of tagged fish to get a better understanding of the population structure. To do so, there is first a need for better understanding the spatial and temporal dynamics of reproduction of ABFT (see above). Trans-Atlantic surveys (using the same sampling protocol throughout the Atlantic and Mediterranean) of both adults and larvae would, thus, be necessary. Furthermore, genetic analyses and micro-chemistry have been recently applied to ABFT to test for the presence of discrete populations between regions of the Mediterranean Sea and North Atlantic. Therefore to build upon these initial successes, it is important to develop protocols and logistic feasibility plans for applying these techniques on large samples encompassing the entire spatial distribution of ABFT. Additionally, these techniques need to be improved so that they can be routinely used to determine the geographical and genetic origins of older individuals, i.e. the spawners.

Genetic tagging is a technique that has recently emerged as a mechanism to estimate population parameters. This technique, that might have potential for application to ABFT, uses genetic markers (DNA) as individual tags. This has two great advantages in comparison to conventional tagging: it avoids most of the post-release mortality and it allows one to obtain an unbiased estimate of reporting rates (e.g. see Palsbøll *et al.* 1997; Taberlet *et al.* 1999). Thus, genetic tagging might constitute an interesting and powerful alternative approach to estimate mortality rates and population sizes of ABFT. It would also provide valuable information to investigate the ABFT population structure. But this technique may require rather extensive (and costly) sampling for both release and recapture. However, the potential for genetic tagging is so promising for ABFT that its feasibility should be explored in near future.

Modelling of ABFT needs to expand beyond the traditional stock-assessment approaches. The renewed importance of spatial dynamics and population structure means that these factors must be

directly dealt with in both the modelling and the management structure. 'Operating models' need to be developed which depict biological, ecological and fisheries 'reality' in detail, exploring a range of hypotheses, e.g. how the population is really structured, how fish move, the sparseness of catch data and other factors. Then management procedures could be developed and tested against the operating models with the goal of deriving management techniques which are robust to data deficiencies and where risks and trade-offs are explored transparently. For instance, if evidences from genetic analyses, micro-chemistry or genetic tagging tend to support a metapopulation structure (see above), then operating models could be designed, so that ABFT would be divided into several corresponding management units (indeed in that case, the traditional two-stock hypothesis would not make sense anymore).

Regardless of the modelling and management mechanisms chosen, there is a need for better monitoring of juvenile abundance and better understanding recruitment dynamics of ABFT. Indeed, abundance signals detected on spawners translate any change in population size with an important delay, due to a late age at maturity. This gives little flexibility to managers. Previously, the feasibility for aerial surveys as a mechanism for monitoring juveniles has been done (Lutcavage *et al.* 1997; Fromentin *et al.* 2003). More integrated approaches using airplanes, vessels and electronic tagging may make monitoring more efficient. Experimental designs and initial pilot surveys should be developed leading to juvenile relative abundance monitoring programmes.

Finally, it would be worthwhile to initiate a data-prospecting and data-recovery effort for the catch composition of the fisheries operating during the 1950s, 1960s and 1970s in the North Atlantic and Mediterranean Sea. The analysis of these data is likely to provide valuable and original insights into ABFT spatial dynamics, as these three decades were marked by remarkable variations in the spatial distributions (possibly abundances) of ABFT in the North Atlantic.

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