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The Journey from Overfishing to Sustainability for Atlantic Bluefin Tuna, Thunnus thynnus

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Abstract :

The Atlantic bluefin tuna, Thunnus thynnus (Linnaeus, 1758), is the largest of the tunas and among the largest of all bony fish, reaching to 3.3 m and 725 kg (Cort et al. 2013). The species is highly migratory and broadly distributed through most of the Atlantic Ocean and its adjacent seas (Figure 1), thanks in large measure to a highly developed thermoregulatory system that allows it to thrive in waters as cold as 3°C (Carey and Lawson 1973, Block et al. 2001). Their great size and power has captivated fishermen and scientists alike since ancient times. Aristotle, Pliny the Elder, and Oppian wrote of them two thousand years ago, and their bones have been excavated from prehistoric sites dating back to the Stone Age (Aristotelis III BC; Plinius 65 CE; Salvini 1738; Ravier and Fromentin 2001; Di Natale 2012, 2014; Puncher et al. 2016). The fascination with Atlantic bluefin tuna (ABFT) has only grown in modern times. The demand for bluefin tuna for the sashimi market in Japan fuels a lucrative commercial fishery where a single fish can be worth tens of thousands of dollars. Researchers passionately pursue investigations on ABFT, writing dozens of scientific papers every year. Public interest in this charismatic species, fanned by warnings of overfishing, has risen to a level usually reserved for whales (Porch 2005). The story of ABFT has been told in compelling documentaries and popular books such as Safina's (1998) Song for the Blue Ocean, Maggio's (2000a,b) Mattanza, and Ellis's (2008) Tuna: A Love Story. They even have their own reality show in National Geographic's Wicked Tuna. As Ellis puts it, ABFT just may be "the worlds best-loved fish."

INTRODUCTION

The Atlantic bluefin tuna, *Thunnus thynnus (*Linnaeus, 1758*)*, is the largest of the tunas and among the largest of all bony fish, reaching to 3.3 m and 725 kg (Cort et al. 2013). The species is highly migratory and broadly distributed through most of the Atlantic Ocean and its adjacent seas (Figure 1), thanks in large measure to a highly developed thermoregulatory system that allows it to thrive in waters as cold as 3°C (Carey and Lawson 1973, Block et al. 2001). Their great size and power has captivated fishermen and scientists alike since ancient times. Aristotle, Pliny the Elder, and Oppian wrote of them two thousand years ago, and their bones have been excavated from prehistoric sites dating back to the Stone Age (Aristotelis III BC; Plinius 65 CE; Salvini 1738; Ravier and Fromentin 2001; Di Natale 2012, 2014; Puncher et al. 2016).

The fascination with Atlantic bluefin tuna (ABFT) has only grown in modern times. The demand for bluefin tuna for the sashimi market in Japan fuels a lucrative commercial fishery where a single fish can be worth tens of thousands of dollars. Researchers passionately pursue investigations on ABFT, writing dozens of scientific papers every year. Public interest in this charismatic species, fanned by warnings of overfishing, has risen to a level usually reserved for whales (Porch 2005). The story of ABFT has been told in compelling documentaries and popular books such as Safina's (1998) *Song for the Blue Ocean*, Maggio's (2000a,b) *Mattanza*, and Ellis's (2008) *Tuna: A Love Story*. They even have their own reality show in National Geographic's *Wicked Tuna*. As Ellis puts it, ABFT just may be "the worlds best-loved fish."

[Fig 1 about here]

THE PAST: A HISTORY OF THE FISHERIES AND MANAGEMENT

Millennia of Atlantic Bluefin Tuna Exploitation

Bluefin tuna have been caught in the Mediterranean and North Seas since the Stone Age. Cave paintings and rock engravings of bluefin tuna found in the Grotta del Genovese on the isle of Levanzo (W. Sicily, Italy) may have been made as many as 11,000 years ago (Tusa 1999, Spoto 2002). Archaeological excavations in Denmark and Sweden have found bluefin tuna remains dating back to 4000-5800 BC (Anon. 2009a). The earliest bluefin tuna fisheries appear to have been prosecuted with hooks and lines, but evolved to beach seines and traps by about the 6th century BCE, mostly in the Bosporus, Marmara Sea, and areas currently belonging to Turkey. Oppian (177 BCE) reported from this area the first description of a tuna trap.

The bluefin tuna trap fishery is one of the oldest documented human industries, dating back at least 27 centuries to the Phoenicians, who maintained trap fisheries in many Mediterranean and Atlantic areas (Fromentin and Powers 2005, Di Natale 2012). The Greeks and Romans further developed this industry, and written records exist dating to the 3rd century BC. Al Idrissi (1154a,b) also wrote descriptions of the bluefin fishery, and the remains of many tuna salting plants have been found from the period. Some of the fishing activities were carried out by large beach seines, and some by typical set traps. Factories from the Byzantine era have been recently discovered in Istanbul (Puncher et al. 2014), and catch statistics from that trap fishery have been recovered back to 1512 (Doumenge 1998, Pagá Garcia et al. in press). Data recently recovered through the ICCAT Atlantic-wide research program for bluefin tuna (unofficially known as GBYP) indicate that bluefin tuna catches from Spanish traps alone were in the order of 14,000 tons (t) in the mid-16th century, and catches of approximately 22,000 t were landed in 1880 by only a fraction of the Spanish, Italian, Portuguese, and Tunisian traps believed to exist at the time (Ravier and Fromentin 2001, Pagá Garcia et al. in press). Given that several traps are likely missing from the statistics, it is possible that total catch in the eastern Atlantic and Mediterranean might be twice that amount and comparable to recent levels.

It is not known if ABFT were as important to aboriginal Americans as they were to Mediterranean cultures, but Pacific bluefin (*Thunnus orientalis*) appear to have been caught along the Pacific coast of North America for more than 5,000 years (Crockford 1997). The earliest recorded commercial landings of bluefin tuna in the Americas date back to the trap and harpoon fisheries operating off New England and Nova Scotia during the early 1900s (Bigelow and Schroeder 1953, Young 1975). In those days ABFT were not highly regarded as food fish. A few were harpooned for oil, but they were mostly regarded as a nuisance because of the damage they would do to traps while in pursuit of mackerel or herring. Gradually, however, local markets developed and the bluefin price increased. By 1946, it had risen to 7–9 cents per pound, and the landings from New England and Nova Scotia increased from a few hundred to nearly 2,000 t (Bigelow and Schroeder 1953). There has also been a long history of sport fishing for bluefin tuna along the eastern coast of the United States. Small bluefin were commonly caught in this area during the mid-1850s, and larger fish were targeted during the 1900s, with the development of heavier tackle. The sport fishery arguably reached its heyday in the late 1930s when anglers like Ernest Hemingway prowled the famed "tuna alley" off Bimini in search of the giant bluefin tuna that once teemed there. Sport fishing for bluefin remains popular today, and a number of tournaments run annually along the U.S. and Canadian coasts.

1.2 Into the New Milennium: An Era of Expanding Fisheries and the Creation of the International Commission for the Conservation of Atlantic Tunas (ICCAT)

Catch statistics are incomplete prior to the 1950s, but the available data suggests catches of 15,000 to 30,000 t per year were taken from traps operating in the Eastern Atlantic and Mediterranean Sea as far back as the 16th century (Fromentin et al. 2014a, Pagá Garcia et al. in press). Traps set in the Mediterranean Sea and in the eastern Atlantic near Gibraltar (to intercept migrating spawners) continued to account for much of the landings through the 1960s (Figure 2), although Norwegian purse seiners operating in the North Sea made sizable catches of large bluefin tuna, as well (typically on the order of 5,000 to 15,000 t; Tangen 2009). There were also important catches of young ABFT by bait boats in the Bay of Biscay and purse seiners off the Atlantic coast of Morocco (Cort 2016). By the late 1960s, the Norwegian purse seine fishery had all but disappeared owing to the collapse of the herring fishery and the diminished local abundance of bluefin (Tangen 2009). Catches from the Mediterranean traps also fell substantially during this time, and by the 1970s, the total landings had dropped to approximately 10,000 t (the lowest levels in recorded history). The cause of these declines has been a matter of some debate, with some hypothesizing changes in migration patterns (Tiews 1978, Fromentin 2009) and others citing evidence of heavy fishing on juveniles after 1949 (Cort and Abaunza 2015, 2016).
[Fig 2 about here]

One the other side of the Atlantic, a purse seine fishery targeting young bluefin tuna for local canneries developed during the 1950s along the eastern seaboard of the United States (Mather et al. 1995). Shortly after, Japanese longliners entered the Atlantic, taking bluefin tuna as bycatch while targeting yellowfin, albacore, and bigeye tuna for canneries (Takeuchi et al. 1999). The combined landings from these two fisheries peaked at almost 20,000 t in 1964, but the fishery off Brazil soon collapsed (perhaps owing to a change in environmental conditions as per Fromentin et al. 2014b), and Japanese longliners abandoned the area for more productive grounds in the eastern Atlantic and Mediterranean. Not long after, small fish became harder to find along the U.S. east coast, causing many purse seiners to stop fishing for bluefin tuna and catches to fall below 700 t by 1968 (Mather et al. 1995). In the West Atlantic, landings for 1968-1970 fell to the lowest levels since the fisheries began.

The drop in catches of ABFT coincided with a generally increasing recognition of the need for international coordination of the study and management of Atlantic tunas. This recognition was formalized in 1966 with the signing of the International Convention for the Conservation of Atlantic Tunas and the establishment of a regulatory commission, the International Commission for the Conservation of Atlantic Tunas (ICCAT), two years later. One of the first recommendations scientists made to ICCAT was to prohibit the capture of bluefin tuna less than ~5 kg, owing to the potential loss of yield (Anon. 1971). The Commission eventually implemented a minimum size limit of 6.4 kg, which effectively reduced the take of young-of-the-year and one- and two-year-old bluefin tuna.

The development of the lucrative Japanese sashimi market during the 1970s was a major turning point for the bluefin fisheries on both sides of the Atlantic. The increasing purchasing power afforded by Japan's rising economy enabled Japanese buyers to offer far more for sashimi-grade bluefin tuna than any of the local fish markets and canneries. Combined with the decrease in the southern bluefin tuna (*Thunnus maccoyii*) catch, the rise in prices allowed Japanese and other distant-water longline fisheries to expand to new grounds and also fueled the rapid expansion of many local fisheries. In the western Atlantic, the local harpoon, handline, and sport-gear fisheries grew rapidly, and purse seiners began to specialize in larger, fatter fish caught late in the season. As a result, the combined landings from western Atlantic fisheries increased to an average of more than 5,000 t. The Japanese sashimi market also fueled a dramatic rise in European purse seine fisheries, although catches fell again after 1976 for a few years when the Commission enacted the 6.4 kg minimum size limit and other regulations limiting fishing mortality.

In 1981, the Standing Committee on Research and Statistics (SCRS) advised the Commission that the western population of ABFT had been depleted, and recommended a major reduction in catch to "as near zero as feasible" (Anon. 1982). Based on this, the Commission agreed to limit catches from western fisheries in 1982 to 1,160 t, although the limit was raised the following year to 2,660 t to adjust for the social and economic hardships experienced by the fishery (Brown and Parrack, 1985). At the same time, ICCAT also increased the minimum size in the western management area to 121 cm, which effectively eliminated the U.S. purse seine fishery for small fish (in 1992 this was decreased slightly to 115 cm and 30 kg). Since then, the catch limits have varied between 1,800 and 2,700 t and reported landings have fluctuated between 1,500 and 3,300 t (Figure 3). The 1981 SCRS also found that the abundance of adults in the eastern population declined by ~50% from 1960 to 1979, but had since increased owing to several strong year classes. The SCRS advised that the eastern bluefin tuna stock seemed to be stable and that current regulations were sufficient. This was not to last, however, in large part because of the rise of the tuna farms.
[Fig 3 about here]

Most adult-sized bluefin tuna have historically been caught during the spawning season when the fat content of the meat is not at its best for the sashimi market. The early farming enterprises focused on fattening large fish caught in traps before shipping them to Japan. The early success of these farming activities caught on quickly, and the market soon took off. By the mid-1990s, farms were widely distributed throughout the Mediterranean Sea (Miyake et al. 2003, Die 2016), and the increased international demand stimulated a corresponding increase in purse seine effort. At the same time, fisheries for small fish increased to supply local markets, and the Japanese longline fleet expanded into the central North Atlantic. By 1996, reported catches had risen to over 50,000 t.

The official catch statistics showed a marked downturn after 1996, but this was an artifact of under-reporting that occurred with the implementation of a total allowance catch (TAC), and catches are believed to have remained as high as 40,000 to 50,000 t (Fromentin 2003, Anon. 2005). Indeed, stock assessments conducted in the 1990s suggested that the recent high catch levels were not sustainable and highlighted an apparent disregard for the 6.4 kg size limit, including substantial catches of young-of-the-year under 1.8 kg (Anon. 1999). Scientists advised that catch levels of 33,000 t or more were not sustainable and that every effort should be made to enforce the 6.4 kg limit. Based on this, the Commission recommended a total allowable catch for eastern fisheries of 32,000 t for 1999 and other management measures designed to curb the capture of very small fish. Similar catch limits were imposed for the next decade, and the declared landings generally fluctuated at levels close to those limits. Unfortunately, evidence was mounting that the true catches of bluefin tuna from the East Atlantic and Mediterranean remained much higher than had been reported. Purse seiners in particular had expanded their fishing grounds to cover the whole of the Mediterranean Sea and were making heavy use of new technologies such as sonar, radar, and aircrafts to detect schools.

1.3 **The Recent Past: A Crisis of Management**

Eastern Atlantic and Mediterranean

The 2006 stock assessment estimated a substantial decline in the biomass of the eastern Atlantic and Mediterranean stock (Anon. 2007), prompting the SCRS to recommend substantial reductions in fishing mortality. In particular, the SCRS advised the Commission to close the Mediterranean bluefin tuna fishery during the spawning season and to raise the minimum size, estimating that a full implementation of these actions would result in a catch of ~15,000 t. The SCRS also warned that the fishing capacity of the eastern Atlantic and Mediterranean bluefin tuna fleet was excessive and that actions had to be taken to reduce the impact of overcapacity as well as illegal fishing. Although the reported catches for 2004 (the last year considered in the 2006 assessment) were 32,567 t, preliminary analyses of fishing capacity suggested the total catch was closer to 50,000 t.

In response to the SCRS advice, the Commission adopted Recommendation 06-05,which established a 15-year recovery plan for the eastern Atlantic and Mediterranean bluefin tuna stock. The main objective of the plan was to ensure the sustainability of the fishery by 2022 with a probability of 60%. The TAC was reduced to 29,500 t in 2007 and stepped down to 25,500 t by 2010; significantly lower than in 2006 (32,000 t), but much higher than the 15,000 t TAC advised by the SCRS. In addition, the Commission established a number of other fishing restrictions including closed fishing seasons, larger minimum size limits, and prohibiting the use of airplanes and helicopters."

The 2007 SCRS report reiterated the advice it provided in 2006, including a 15,000 t TAC (Anon. 2008). Nevertheless, in 2007 the Commission did not adopt any new management measures for eastern Atlantic and Mediterranean bluefin tuna, and the TAC remained unchanged. The 2008 stock assessment confirmed the results from the 2006 assessment, estimating that the current fishing mortality rate was 3 times higher than the level that would permit the stock to stabilize at the maximum sustainable yield (MSY) level (Anon. 2009b). The SCRS acknowledged the positive steps taken previously by the Commission, but once again advised a TAC of ~15,000 t. Perhaps more importantly, the SCRS formally confirmed widespread suspicions of illegal, unreported, and unregulated fishing. Catches from the mid-1990s through 2007 were estimated to be on the order of 50,000 t to 61,000 t, nearly double what had been officially reported (SCRS 2009b). In response, the Commission extended the seasonal closures, froze fishing capacity and imposed measures to adjust farming capacity. The TACs were also reduced (to 22,000 t, 19,950 t, and 18,500 t, for 2009-2011, respectively), although not to the level recommended by the SCRS.

Two significant events occurred in 2009 that raised the stakes for the Commission: First, a proposal to list Atlantic bluefin tuna under Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) would have precluded any international trade for this species, and second, a report from an independent panel of experts contracted by ICCAT to review its performance concluded the management of eastern Atlantic and Mediterranean bluefin tuna was 'widely regarded as an international disgrace' (Anon. 2009c). These two factors, combined with mounting pressure from many stakeholders, non-governmental organizations, and advice from the SCRS warning of potential fishery collapse, spurred the Commission to reduce the TAC to 13,500 t (which for the first time was commensurate with the scientific advice). Moreover, closed seasons were further extended, fishing capacity was again reduced and monitoring and control measures were strengthened considerably.

Despite the conclusion of the Food and Agriculture Organization of the United Nations (FAO) panel of experts that bluefin tuna stocks met the biological criteria to be listed under the Appendix I of CITES, the proposal was ultimately defeated at the CITES meeting in March 2010. However, there is little doubt that the threat of listing bluefin tuna under CITES pressured the Commission to finally adopt meaningful management measures for eastern Atlantic and Mediterranean bluefin tuna. Arguably, the adoption of these measures by the Commission in November 2009 was a major reason for the rejection the CITES listing.

Western Atlantic

The management and the fisheries of western and eastern bluefin tuna differ in a number of ways (Figure 3). The SCRS has never detected substantial illegal or unreported catches on the western bluefin tuna fisheries and the TACs adopted include both landings and dead discards. As a result, the monitoring and compliance measures for the western bluefin tuna fisheries are not as rigorous as for the eastern stocks.

The management advice provided by the SCRS on the basis of the 2006 stock assessment indicated that the TAC of 2,700 t [adopted in Recommendation (Rec.) 02-07] would result in stock declines of approximately 3% per year, whereas a TAC of 2,100 t would allow the stock to increase at approximately 1.5% per year, and TAC of 2,300 t would maintain the stock at the 2006 level (Anon. 2007). In response, the Commission adopted Recommendation 06-06, which reduced the TAC from 2,700 t to 2,100 t for 2007 and 2008 and maintained other fishing limitations. The 2007 SCRS acknowledged that this reduction in TAC was a step in the right direction, but warned that the management regulations in place might be insufficient to rebuild the stock to MSY levels (Anon. 2008).

A new stock assessment was conducted in 2008, and on the basis of the results, the SCRS strongly advised against an increase in TAC (Anon. 2009b). The SCRS expressed concern that the rebuilding plan had been unsuccessful inasmuch as the biomass halfway through the rebuilding period was still below the level when the plan was initiated. As such, the SCRS advised the Commission "to adopt more conservative catch levels that will result in a higher probability (for example, 75% chance) that B_{MSY} is achieved by the beginning of 2019." The SCRS indicated that, for example, under the more optimistic low-recruitment scenario, this target might be achieved with a TAC of 2,000 t. However, they also pointed out that the appraisal was much less optimistic when the index for the small Gulf of St. Lawrence fishery was excluded from the assessment, suggesting a TAC of 1,500 t or lower might be necessary. Moreover, under the high-recruitment scenario, rebuilding could not have been achieved during the expected time frame even with zero catches. Responding to the SCRS, the Commission reduced the TAC for years 2009 and 2010 to 1,900 t and 1,800 t [Rec. 08-04]. The following year, the SCRS commented that the TACs adopted by the Commission in Recommendation 08-04 had less than a 50% chance of meeting the target under the "high- recruitment scenario" (Anon. 2009b).

2. THE CURRENT SITUATION

2.1 **The Two-Stock Hypothesis and Potential Importance of Mixing**

Stock assessments of ABFT have relied heavily on virtual population analyses (VPAs), although a number of other models have been considered. The first VPA was conducted in 1974 and treated the entire Atlantic population as a single stock. However, even at that time, there was evidence from tagging data, larval surveys, and fishery patterns that there might be at least two intermixing stocks. The overall sentiment of the SCRS at the time was that, while the evidence was weak, it favored the hypothesis of separate eastern and western stocks with a small and variable interchange (Anon. 1982). To protect the apparently flagging western stock, the Commission formally recommended (Rec. 81-01) that CPCs take steps to prohibit the capture of bluefin tuna in the western Atlantic Ocean as defined by the equal-distance line shown in Figure 1 (Anon. 1982, p. 88). The SCRS has used this equal-distance line to delineate the eastern and western stocks ever since, but always with the caution that a failure to adequately manage either stock could have serious repercussions on the other (Anon. 1980).

The assessments in 1978 and 1981 analyzed the two putative stocks separately as well as combined; the end result was a recommendation to substantially reduce western catches (Anon. 1980, 1982). Over the next decade, subsequent assessments benefited from better data and a longer time series, but essentially employed the same methods and drew considerable criticism because bluefin tuna had often been observed to move from one side of the Atlantic to the other. However, as Brown and Parrack (1985) pointed out, the question is not whether there is interchange, but whether there is enough interchange to invalidate the two-stock designation for management purposes.

The SCRS began quantifying the possible implications of various interchange hypotheses in 1993 by use of a two-area virtual population analysis model (Anon. 1994, Butterworth and Punt 1994, Punt & Butterworth 1995). These early analyses showed that interchange rates of even a few percent could have a substantial impact on appraisals of the western stock status. Shortly thereafter, the U.S. National Research Council (NRC) independently estimated the rates of interchange from tag-recapture data and showed that estimates of the abundance of mature fish in the western stock were higher with those interchange rates than when no interchange was assumed (NRC 1994). Subsequently, the ICCAT Commission resolved that the SCRS should develop recovery options for bluefin tuna that take into account the possible effects of mixing.

The two-area model used by the SCRS and the NRC during the early 1990s assumed that fish movement depended on where the fish was located, essentially implying that fish moving from one side of the ocean to the other “forget” where they came from (the so-called “diffusion” or “no- memory” model). However, the SCRS expressed concern that such a model is an unlikely characterization of bluefin tuna migration and that it may be more likely that bluefin tuna return to the area where they were born (Anon. 1995, p. 108-110). Cooke and Lankester (1996) suggested a possible alternative in which the ranges of the eastern and western populations are assumed merely to overlap, which would imply that fish “remember” which side of the ocean they come from and how to return. They found that this “overlap” model was at least as consistent with the tagging data as the diffusion model. Several fairly extensive investigations have since been conducted on the performance of the diffusion and overlap models when the interchange rates are estimated within the VPA from tagging and stock composition data (Porch et al., 1995, 1998, 2001;, Anon. 2009d). These studies have generally found that the estimates of abundance were similar to those obtained conducting two separate VPAs, except in simulations where the mixing rates were large and of a diffusive nature. Otherwise, the results tended to be more sensitive to parameters such as the natural mortality or the type of data used to “tune” the model (e.g., whether tagging data was used or not) than to the specific nature of the mixing model.

The most recent investigation of the effect of mixing on the VPA results was conducted during the 2008 SCRS stock assessment (Anon. 2009d). When stock composition data (derived from otolith microconstituent analyses; Rooker et al. 2008, Fraile et al. 2015) were used to estimate the degree of overlap between the two stocks, the estimates of stock status for both the eastern and western populations were very similar to the estimates obtained from the corresponding VPAs that ignored overlap. However, when conventional tagging data were used to estimate the overlap, the estimates of recent stock status were more optimistic for both the east and west. In effect, the stock composition data, while a more direct measure of the effect of interchange between the two stocks, contains little additional information that would affect other parameters estimated by the VPA (such as the fishing mortality rates on the oldest age class). Tagging data, on the other hand, potentially contains a great deal of information on fishing mortality rates and other parameters, and therefore has a greater impact on the VPA results.

Other models have been developed that use electronic tagging data to estimate interchange and stock status. For example, Taylor et al. (2011) introduced the multi-stock age-structured tag-integrated stock-assessment model (MAST) of ABFT, which used extensive tagging data as well as stock composition derived from otolith microchemistry. Their appraisals of the western stock indicated that only strong catch limitations for western and eastern stock could enable the stock rebuilding. Although the SCRS did not consider these models to be ready for use as a source of management advice, it did note that it was a useful tool to help identify research priorities for future assessments.

The SCRS noted the stock composition and tagging data available at the time were incomplete and not necessarily representative of the entire population, as most of fish have been tagged in the western Atlantic Ocean. They concluded that the analyses of the effects of mixing were not yet reliable enough to use as the basis for the Commission's rebuilding plans for the eastern and western ABFT. Accordingly, subsequent assessments continued to focus on conducting separate assessments of the two stocks with the perennial caveat that “management actions taken in the eastern Atlantic and Mediterranean are likely to influence the recovery in the western Atlantic, because even small rates of mixing from East to West can have considerable effects on the West due to the fact that eastern plus Mediterranean resource is much larger than that of the West” (Anon. 2015a).

It should be noted that a great deal of progress has been made in recent years, both in the information that is available about mixing and in models that are flexible enough to utilize the diverse types of data now available (conventional tagging, electronic tagging, otolith micro-chemistry, and genetics; Carruthers et al. 2016). Evidence has increased in support of the notion that there are two main stocks that overlap in time and space, and it is expected that these new developments will contribute heavily to the upcoming assessment in 2017.

2.2 **A Brief Review of Current Methods: Virtual Population Analysis with Two Independent Stocks**

The most recent assessment of ABFT was conducted in 2014. The projections were updated in 2016 using the specifications of the 2014 assessment and the realized catch in 2014 and 2015. The primary analytical tools used for management advice were tuned single-stock VPAs, which were implemented using program VPA-2BOX, and forecasts, which were implemented using program PRO-BOX (Porch 2002). The VPA approach used here is fundamentally based on a series of extensions to the method of Parrack (1986), widely referred to as the ADAPT framework (Powers and Restrepo 1992, Porch 2002). The method assumes that the catch history of any given year class is known with little error, permitting the historical abundance and fishing mortality rates to be computed deterministically from an estimate of the fishing mortality rate on the oldest (terminal) age of the year class. The estimates are then refined in an iterative process until the best fit is achieved to time series of relative abundance (a process often referred to as tuning). The key parameters of the VPA implemented in the VPA-2BOX software include the fishing mortality rate on the oldest age class (expressed as a multiple of the fishing mortality rate on the next younger age, the F-ratio), the fishing mortality rate on each age class in the last year, the natural mortality rate at age, the scaling coefficients relating indices of relative abundance to absolute abundance (catchability coefficients), and the standard error of each abundance index. The specifications for the 2014 assessments of the two ABFT stocks are summarized below, and a more detailed description is available in the original SCRS assessment document (Anon. 2015b).

Western Atlantic stock: data and methods

The primary catch statistics (Figure 2) come from four major fishing nations: Japan, the United States, Canada, and Mexico. Catch-at-size data were particularly scarce prior to 1970; therefore, the 2014 assessment was based on data from 1970 through 2013. Unfortunately, age-length keys were not available for bluefin tuna until very recently (2016), therefore the catch-at-size data had to be converted to catch-at-age data by using a version of cohort slicing (a method that uses a growth curve to convert size to age, which is generally regarded as less accurate than an age-length key). The low number of samples and use of cohort slicing suggest that the resulting catch-at-age matrix may be relatively error prone, in which case a statistical catch-at-age model may be more appropriate. However, over the years, a number of authors have applied various forms of statistical catch-at-age and catch-at-size models to ABFT (e.g., Porch 1996, Porch et al. 1994, Butterworth and Rademayer 2015, Taylor et al. 2011), and in many cases the results were less sensitive to the choice of statistical models than to other key drivers such as the natural mortality rate.

Twelve indices of abundance covering different life history stages were used in the assessment, including two fishery-independent indices (see Table 9 in Anon. 2015b). Information for some of the indices no longer exists, but a number of them have been updated through 2015 (Figure 4). The catch rates of juvenile bluefin tuna (ages 2-3) in the U.S. rod and reel fishery suggest strong year classes in 2002 or 2003, but none since. The catch rates of adults in the U.S. rod and reel fishery decreased between 2011 and 2013, but increased somewhat in the two years since the assessment. Catch rates of the Japanese longline fishery fluctuated substantially over time, peaking in 2012 and declining thereafter (although they remain higher than the average in the 1990s and early 2000s). The catch-rate series from the U.S. Gulf of Mexico longline fishery shows no clear trend prior to 1991, but a generally increasing trend since the early 1990s, with a peak in 2012 followed by a small decline. The indices for the Gulf of St. Lawrence show the most dramatic rise, and the SCRS questioned if such an increase was biologically plausible for the stock as a whole, noting that other factors may not have been accounted for (changes in stock distribution, management regulations, fishing behavior, and environment). The Gulf of Mexico larval survey (the only active fishery independent indicator) has fluctuated around relatively low levels since the 1980s, although 2011 and 2013 were relatively high.

[Fig 4 about here]

The tuned VPA tracked the abundance and mortality of each age-class from 1970 through 2013, where the oldest age-class a plus-group (ages 16 and older). The natural mortality rate was assumed age-independent at 0.14 yr^{-1} and the fishing mortality rate on the plus-group was set equal to that at age 15 for the entire period (it was determined that selectivity was unlikely to differ on fish age 15 and older because growth is relatively slow at this age and all animals are likely mature). The fishing mortality rates for each age in the last year were estimated with a mild constraint restricting the amount of change in the vulnerability pattern during the most recent three years. Projections (forecasts) of the abundance of the western stock under a variety of possible catch scenarios were based on the bootstrap replicates of the fishing mortality-at-age and numbers-at-age matrices produced by the VPA-2BOX software. Projections and benchmarks were computed for two scenarios of potential future recruitment (Figure 5): A low-recruitment scenario (two-line model) that assumes average recruitment cannot reach the high levels from the early 1970s (ostensibly owing to a change in the environment), and a high-recruitment scenario that assumes the number of recruits is a Beverton and Holt function of the spawning biomass in the previous year. Medium-term projections were conducted to cover the time of the rebuilding plan (2019). Projected levels of spawning stock biomass (SSB) were expressed relative to the SSB associated with the maximum sustainable yield (SSB_{MSY}, the current target of the ICCAT rebuilding plan) corresponding to each of the two recruitment scenarios.

[Fig 5 about here]

Eastern Atlantic and Mediterranean stock: data and methods

The catch statistics (Figure 2) for the eastern Atlantic and Mediterranean represent a variety of fisheries from nearly 50 countries. Since the 1980s, the bulk of the catch has been taken by purse seiners, mostly for the farming industry (especially France, Italy, Spain, Croatia, and Turkey), although trap, bait boat and longline fisheries have remained important. Unlike the west, the catch statistics for the east are believed to be reasonably good from 1950 through the early 1970s. However, it became increasingly difficult to obtain representative size samples from the purse seine fleets in the Mediterranean as more and more of the catch was destined for farming operations. Much of the catch-at-size information has therefore been constructed using a variety of substitutions based on sparse samples borrowed from other fleets, or in the case of purse seiners, on observations of mean individual weights. Moreover, as mentioned previously, the SCRS estimated that the catches by purse seiners and other fleets were substantially greater than had been declared to ICCAT. Indeed, the situation was of such concern to the SCRS that a VPA was not conducted during 2006, and analyses focused instead on the pieces of data that were thought to be most reliable (Fromentin et al. 2007). It is worth noting that the situation has improved in recent years, especially since 2014, when ICCAT mandated the use of stereoscopic cameras to estimate the size frequency at caging (with errors of less than 5%).

The SCRS went back to using VPA during the 2008 assessment, owing in part to the Commission's directive to provide Kobe matrices quantifying the probability that the stock would rebuild under various constant catch levels and in part to the need for a common platform for stock mixing analyses. The 2014 assessment was conducted using data from 1950 through 2013, but considered two catch scenarios, one based on the declared catch and the second based on independent estimates made by the SCRS (i.e., the inflated catch scenario—50,000 t from 1998 to 2006 and 61,000 t in 2007, and reported catches thereafter). Age-length keys were not available, and the catch-at-size data had to be converted to catch-at-age data using cohort slicing (as with the western Atlantic stock, and with the same concerns).

Six indices of abundance were used to tune the base VPA in 2014 (Figure 4; see also Table 6 of Anon. 2015a): catch-per-unit-effort (CPUE) data for Norwegian purse seiners in the North Sea (ages 10+), Spanish and Moroccan traps in the Mediterranean (ages 6+), Moroccan traps alone (ages 6+), Japanese longliners in the Northeast Atlantic (ages 4+), Japanese longliners in the East Atlantic and the Mediterranean Sea (ages 6+), and Spanish bait boats in the Bay of Biscay (ages 2-6, depending on the year). The Norwegian purse seine fishery no longer exists, and the remaining indices have been affected by recent regulation-induced changes in the operational patterns of the fishery or the size of fish being targeted. The changes were particularly profound for the Spanish bait boat index of juvenile fish, which had to be treated as a new index after the adoption of the recovery plan and then was updated using French bait boat data from 2011 to 2014 because the Spanish bait boat fishery sold most of its bluefin tuna quota. The bait boat index was effectively discontinued after 2014 as the number of French bait boats operating was too low to ensure the reliability of this index (the quota transfer ended in 2016, and this index may hence be continued). The most influential series in the assessment were those derived from the Japanese longline fishery in the northeast Atlantic and the Moroccan and Spanish traps, which suggested sharp increases in the abundance of large fish in recent years. Interestingly, these two indices have shown significant downturns since the 2014 assessment (Figure 3).

The VPA for the eastern stock set the plus-group to age 10 and the natural mortality rate *M* varied with age according to estimates derived from tagging data for southern bluefin tuna (0.490, 0.240, 0.240, 0.240, 0.240, 0.200, 0.175, 0.150, 0.125, 0.100 yr^{-1} for ages 1 to 10+, respectively; Hampton 1991). The F-ratios were fixed to values defined during the 2010 assessment based on independent analyses of changes in the size composition of large fish: 0.7 for 1950-1969, 1.0 for 1970-1984, 0.6 for 1985-1994, and 1.2 from 1995 onwards. Projections and benchmarks were computed for the two sets of historical catch estimates (reported and inflated), three scenarios of potential future recruitment (the high average recruitments estimated for 1990-2000, the medium average for 1955-2006, and the low average during 1970-1980), and two selectivity patterns (geometric mean of the relative fishing mortality rate estimates over 2007-2009 or 2009-2011). Medium-term projections were conducted to cover the time of the rebuilding plan (2022). Projected levels of SSB were expressed relative to the SSB associated with the level corresponding to F0.1 (the proxy selected for estimating MSY).

2.3 **Estimated Stock Status and Outlook**

Western Atlantic stock

The base VPA model from the 2014 assessment estimated that SSB of the western Atlantic stock had decreased rapidly from 1970 to 1992, but then began to stabilize, fluctuating without trend through the turn of the century (Figure 6). The estimates for more recent years indicate a gradually increasing trend through 2013, when SSB was estimated to be about 55% of the level estimated for 1970, thanks in part to a strong 2002-2003 year class. The perceived status of the stock relative to the level that corresponds to MSY depends on the assumption about future recruitment (Figure 7). Under the low-recruitment scenario, the stock appears to be neither overfished nor undergoing overfishing; recent levels of F were ~36% of F_{MSY}, and SSB was about twice SSB_{MSY}. Under the high-recruitment scenario, the stock also did not appear to be undergoing overfishing ($F_{(2010\text{-}2012)}$ = 88% of F_{MSY}), but was severely overfished (SSB_{2013} = 48% of SSB_{MSY}).

The projections of stock status suggest that if the low-recruitment scenario is correct, catches of 2,500 t or lower would maintain the stock above the SSB_{MSY} level, and constant catches of 2,250 t would cause the stock to decline somewhat initially, but allow a recovery to the 2013 level by the end of the rebuilding period (2019). If the high-recruitment scenario is correct, then the western stock would be highly unlikely to rebuild by 2019 even with no fishing, although catches less than 2,500 t are predicted to prevent overfishing (Table 1).

[Fig 6 about here]

[Fig 7 about here]

[Table 1 about here]

The SCRS has long recognized the sensitivity of the conclusions regarding stock status, but has been unable to resolve the issue owing in part to the lack of information for the early years of the fishery, when exploitation was low and stock status was presumably higher, and in part to the large interannual variation in recruitment that typically plagues attempts to discern the nature of the spawner-recruit relationship in wild populations. Thus, the SCRS has typically included language to the effect of "The Committee has insufficient evidence to favor either scenario over the other and notes that both are plausible (but not extreme) lower and upper bounds on rebuilding potential." Nevertheless, the conclusion that overfishing has ended appears to be robust across recruitment scenarios, suggesting that the western stock will eventually rebuild to near the true level of MSY even if the high-recruitment scenario is more correct, albeit well after the Commission's prescribed rebuilding period.

Eastern Atlantic and Mediterranean stock

The 2014 assessment results estimated that SSB declined from ~300,000 t prior to the 1970s to ~150,000 t in the mid-2000s. The estimates for more recent years, however, suggest that SSB has increased rapidly to ~500,000 t in 2013 (Figure 8). Estimates of the fishing mortality rate (F) on younger fish (ages 2-5) increased until 2008 and then fell sharply (Figure 8), presumably owing to the minimum size regulations under Recommendation 06-05. The fishing mortality rate on older fish (ages 10+) appeared to decrease during the first two decades and then rapidly increased after 1980 as the fishery grew to supply farms fattening bluefin tuna for the growing Japanese sashimi market. Recent levels appear to have declined owing to stricter adherence to the various management measures in place (including much lower TACs).

Although the data and resulting estimates are regarded as highly uncertain, they are qualitatively consistent with the improvement in stock status expected under current regulations. Whereas the perception of the stock status relative to the MSY proxy ($F_{0.1}$) is sensitive to the assumptions regarding the future selectivity pattern and recruitment levels, overall there was little indication of overfishing and a reasonable chance that the stock may no longer be overfished. For example, under the medium-recruitment scenario, the estimates of F_{2013} were below the reference target in the majority of runs (the median estimates of $F_{2013}/F_{0.1}$ were 0.4 and 0.36 for the reported and inflated catch scenarios, respectively), and the estimates for SSB were generally above the level expected at $F_{0.1}$ ($SSB_{2013}/SSB_{0.1}$= 1.10 and 1.11 for reported and inflated catch scenarios, respectively). The projections of stock status suggest that if future catch is limited to 30,000 t or less, there is greater than a 60% probability that F would remain below $F_{0.1}$ and that SSB would meet or exceed $SSB_{F0.1}$ by the end of 2022 (Figure 9 and Table 2).

[Fig 8 about here]
[Fig 9 about here]

[Table 2 about here]

It is important to note that the rapid rise in estimates of SSB is driven by the recent trends in the two fishery-dependent indices of abundance for older fish—Japanese longlines and Spanish/Moroccan traps. To fit these indices, the VPA estimated that the year classes in 2004-2007 were substantially larger than the 2003 year class. However, no independent evidence has been offered to substantiate the existence of such extraordinarily large year classes, anecdotal or otherwise. For example, the 2003 year class can be easily tracked in the size frequencies of catches from the Japanese longline and other fisheries (Suzuki et al. 2013). If the 2004-2007 year classes were as large as estimated, they should have been evident in the most recent size-frequency information. Inasmuch as there are reasons to suspect that the sharp increase in the trap and longline indices may in part be a consequence of the reduced spatial scales in which they operate and perhaps other changes in fishing practices in response to the reduced quotas, the SCRS advised caution in interpreting the results until the high estimates of recruitment could be better verified. The SCRS also noted that two other assessment models and some sensitivity analyses of the VPA did not estimate such high recruitments or as rapid an increase in recent SSB. Perhaps more importantly, the two key indicators of stock abundance (Moroccan trap and Japanese longline indices) have trended downward since the last assessment, suggesting the projected increases may be overly optimistic.

2.4 **Current Management**

The extraordinary amount of IUU (Illegal, Unreported, and Unregulated) fishing for bluefin tuna in the Mediterranean Sea brought to light by the nongovernmental organizations and the SCRS eventually led to a number of important measures to better track and control the catches of ABFTs and a strengthening of the function of the ICCAT Commission's Management Measures Compliance Committee. Many of these measures are detailed in Recommendation 14-04, a 35-page document with 103 operative paragraphs and 11 annexes (in contrast, Recommendation 14-05 for western ABFT, where substantial IUU has not been identified by the SCRS, is only 5 pages long with 28 operative paragraphs and no annexes). The new measures include a requirement for CPCs to reduce their fishing effort commensurate with their individual allocation, including the establishment of individual quotas for vessels over 24 meters. The Commission also required CPCs fishing for eastern Atlantic and Mediterranean bluefin tuna to develop annual fishing plans that identify the quota allocated to each fishing fleet, how the quotas were allocated, and the measures taken to ensure compliance with these quotas. Several indirect controls were also developed to control fishing effort and to reduce potential IUU, the most important of which were reductions in the duration of the fishing seasons allowed for each fleet. Of particular significance was the restriction of purse seine fleets to just one month as purse seiners account for approximately 80% of the total bluefin tuna catch in the Mediterranean Sea.

Other measures were introduced to better track bluefin tuna catches. For example, the Commission prohibits any domestic trade, landing, import and exports, caging operations, and re-exports that are not accompanied by accurate and validated BCD, which was made electronic (eBCD) in 2016.

The total allowable catch for the eastern Atlantic and Mediterranean Sea from 2010 to 2014 was drastically reduced from the prior decade (ranging from 12,900–13,400 t (Recs. 09-06, 13-07), which in combination with other regulations appears to have led to a substantial improvement in the status of the eastern stock. Nevertheless, the uncertainty associated with the 2014 stock assessment led the SCRS to be somewhat equivocal in its advice. The SCRS indicated that "maintaining the 2014 TAC (13,400 t.) or gradually increasing it should not undermine the success of the rebuilding plan for the eastern Atlantic and Mediterranean stock." The SCRS was unable to reach consensus on the upper limit for such an increase that would not jeopardize the recovery of this stock, but did advise that "a gradual increase (in steps over e.g., 2 or 3 years) of the catch to the level of the most precautionary MSY estimate would allow the population to increase even in the most conservative scenario (low recruitment scenario)." The most precautionary MSY for the eastern Atlantic and Mediterranean stock was estimated by the SCRS to be 23,256 t (corresponding to the low-recruitment scenario with the reported catch data). Based on this advice, the Commission set the TACs for 2015, 2016, and 2017 at 16,142 t, 19,296 t, and 23,155 t, respectively (Rec. 14-04) with an additional quota of 500 t for Algeria in 2017.

The results of the western Atlantic stock assessment also showed an increase in SSB over the last few years of the times series used. The SCRS indicated that the strong 2002/2003 year classes and the reduction in fishing mortality contributed to this trend. Considering the uncertainties regarding the future productivity of the stock (i.e., future potential recruitment levels) and the possible effects of mixing with the eastern stock, the SCRS advised that a TAC of 2,250 t was not expected to result in stock growth by 2019, and as such, it should not be exceeded. In contrast, the 2013 TAC of 1,750 t would allow for the SSB to increase more quickly, which in turn might help to resolve the high- and low-recruitment hypothesis. Considering the SCRS recommendation for the western ABFT stock, the Commission increased the TAC to 2,000 t for 2015 and 2016 (Rec. 14-05).

3. THE FUTURE: RESOLVING THE UNCERTAINTIES FOR BETTER ASSESSMENTS AND MANAGEMENT

Scientists and stakeholders have identified a number of uncertainties affecting the assessment and management of ABFT (e.g., Fromentin et al. 2014a, Leach et al. 2014). Among the earliest and most frequently cited concerns has been the issue of stock structure and degree of intermixing. Since before the inception of ICCAT, it was recognized that bluefin tuna frequently made transatlantic migrations and that there were at least two major spawning grounds (one in or near the Gulf of Mexico and one in or near the Mediterranean Sea). Today, the weight of the evidence appears to confirm the hypothesis of two main stocks, but questions remain regarding alternative spawning grounds (e.g., Mather et al. 1995, Piccinetti et al. 2013,; Richardson et al. 2016) and potential subpopulations or contingents within the Mediterranean (see Arrizabalaga et al. 2017). Moreover, several electronic tagging studies suggest the rate of interchange may be higher than previously thought (Block et al. 2005, Walli et al. 2009, Galuardi et al. 2010, Carruthers et al. 2016). Otolith microchemistry studies show that fish originating from the Mediterranean account for a substantial proportion of catches in some western fisheries (e.g., Rooker et al. 2008, Siskey et al. 2016), and, in some years, fish originating in the Gulf of Mexico may account for a significant proportion of the catch in some eastern Atlantic areas (Di Natale and& Tensek 2016).

The Commission and others have recommended moving toward the use-assessment models that account for stock mixing explicitly. However, the efficacy of these mixing models is compromised by the generally poor quality of the fishery data in the Mediterranean Sea since the advent of farming. If the assessments of the western and eastern populations are linked through a mixing model, then the uncertainties associated with the Mediterranean fishery data will be propagated through to the western stock assessment. Thus, it is unclear if the assessment of the western stock would actually be improved by the use of a mixing model, even if the mechanism and magnitude of mixing were known perfectly. If, in addition, the mixing model were misspecified, the resulting assessment could be more biased than an assessment that does not account for mixing at all (Porch et al. 1998).

The future recruitment of young fish to the population has been another major source of uncertainty for ABFT assessments. As for many other exploited species, the relationship between spawners and the number of young fish recruiting to the population has been difficult to discern. The combination of high natural variations in recruitment and lack of contrast in the available data (the time series of catch and relative abundance data begin well after both stocks had been reduced by exploitation) poses a difficult statistical challenge in and of itself. Considering also the error-prone nature of the available data and nonstationary nature of the spawner-recruit relationship, one must conclude that the true nature of the spawner-recruit relationship will not be resolved for some time. Past assessments of the eastern and western Atlantic stocks have tackled this issue by examining the implications of alternative recruitment hypotheses that are considered to bracket the range of possibilities (see section 2.2)., However, a more fruitful course may be to focus instead on adopting biological reference points and management procedures that are robust to this and other sources of uncertainty (Porch and Lauretta 2016).

A related issue, and subject of considerable controversy, is how best to index the number of eggs produced by each stock. The assessments for both assume that the number of eggs produced is proportional to mature biomass. Recent studies seem to support that approach in that they suggest batch fecundity per unit of body weight is fairly constant (e.g., Correiro et al. 2005, Aranda et al. 2013, Knapp et al. 2015). However, the assessments differ markedly in their choice of maturity schedules, with the western assessment assuming that all fish are fully mature beginning at age 9 (on the basis of the age composition of fish caught on the Gulf of Mexico spawning ground) and the eastern assessment assuming that 50% of the fish are mature at age 4 and all fish by age 5 (on the basis of histological analyses of fish caught on Mediterranean spawning grounds). The SCRS has long recognized that actual maturity schedules are unlikely to be so disparate between the stocks, particularly given the similarity in their rates of growth. Indeed, there is some recent evidence that suggests some western-origin fish may mature as early as age 3 (Heinisch et al. 2014, Richardson et al. 2016). However, in the case of batch spawners like bluefin tuna, the important quantity is not maturity but spawning frequency (and perhaps egg quality). The use of mature biomass as a proxy for spawning output presumes that all mature fish are equally successful, i.e., young fish spawn just as often with as high quality of eggs as older fish. This contention has not been well established for large pelagic fish. To the contrary, histological and close-kin genetic analyses of southern bluefin tuna suggest that older fish contribute substantially more to the spawning output of the population than what would otherwise be expected because of their weight (Farley et al. 2015, Bravington et al. 2016).

One of the most influential parameters in a stock assessment is the natural mortality rate *M*, which is notoriously difficult to estimate within a stock assessment unless the data are available from a well-designed mark-recapture study, or the available indices of abundance and age-composition data cover a period when fishing was negligible. Inasmuch as neither situation has been true for ABFT, the SCRS has based *M* values for the western stock on results of a tagging study (Farber 1980), and for the eastern stock, on estimates for southern bluefin tuna (Fonteneau and Maguire 2014). In view of the fact that the growth rates and habitats are similar for both stocks, the SCRS has recently proposed replacing these assumptions with a single common vector based on the Lorenzen (2000) mortality function of weight ($M=3.0.W^{-0.288}$, where *W* is the weight-at-age of individual fish) rescaled so that the mortality rate on the oldest ages plateaus at 0.1 (the value used previously for the eastern stock).

Two large research programs have developed in recent years targeting international research on ABFT to address these uncertainties among others. The largest of these is the ICCAT Atlantic-wide research program for bluefin tuna (unofficially known as the GBYP) with an annual budget of ~2 million euros (http://www.iccat.int/GBYP/en/). The program was officially adopted by the ICCAT Commission in 2008 and implemented in 2010 with the following priorities:

1. Improve basic data collection.
2. Improve understanding of key biological and ecological processes.
3. Improve assessment models and provision of scientific advice on stock status.

The GBYP has generally emphasized research in the eastern Atlantic and Mediterranean Sea, in tacit recognition of the Bluefin Tuna Research Program (BTRP) administered by the United States, which has similar goals, but focuses on the western Atlantic (albeit with a smaller budget of ~$650,000 per annum).

These GBYP, BTRP and other research programs have produced a great deal of new information that promises to fundamentally change the assessment and management of ABFT. One of the greatest successes has been the collection of tissues and development of methods to determine the origin of fish from genetics, otolith microchemistry and otolith shapes (e.g., Fraile et al. 2015, Rooker et al. 2014, Puncher et al. 2015, Brophy et al. 2015, Rodriguez Ezpeleta et al. 2016; see also the chapter by Rooker and Secor in this book), and the calibration of techniques to determine ages from both otoliths and spines (Rodriguez-Marin et al. 2012, 2016). For the first time, it has become feasible to prepare age-length keys by stock of origin, which can be applied to length samples to discern the stock of origin and age composition of the catch (Anon. in press).

Another important success has been the recovery of data from the eastern ABFT fisheries using market data, stereoscopic cameras, and other sources of information to recreate the magnitude and size frequency of the catch since the farming era(Anon. in press). Several new indices of abundance have also been developed for possible use in the 2017 assessment, . including an acoustic survey of adult bluefin in the Gulf of St. Lawrence (Melvin 2015), an aerial survey for juvenile bluefin tuna in the Northwest Mediterranean Sea (Bauer et al. 2015), a larval survey in the Balearic Sea (Ingram et al. 2015), and an aerial survey of adult bluefin covering much of the Mediterranean Sea. In addition, scientists from Canada, Japan, Mexico and the U.S. have jointly developed the most comprehensive collection of set-by-set longline data for western ABFT yet compiled and plans are underway to develop a combined index that will cover a large fraction of the fishable habitat.

Arguably the greatest investment has been made in various mark-recapture experiments because they potentially provide needed information on most of the variables of interest for stock assessments (population size, mortality rates, movements, growth, etc.). More than 24,000 conventional tags and nearly 1,500 electronic tags have been released across the different programs since 2010, and nearly 1,000 electronic tag tracks have been compiled that the SCRS will use to inform movement models (Hanke et al. 2016).

A number of efforts are underway to develop more realistic models that can better utilize all the new information described above for stock assessments and management strategy evaluations. One approach (Cadrin et al. unpublished) incorporates stock mixing implicitly by applying the VPA to the catch at age of western-origin fish only (parsing the total Atlantic catch using otolith-derived stock composition information). This approach effectively focuses on the western stock and avoids the need to estimate the level of intermixing between stocks, butthe data are rather sparse prior to 2010 and the fraction of the catch that is of western origin is not well -determined. Other recent modeling efforts are focusing on developing statistical catch-at-length models to make better use of the available size and age data and to move away from cohort slicing (Irie and Takeuchi 2015, Butterworth and Rademayer 2015, Walters and Calay, unpublished).

Perhaps the most valuable contribution of the GBYP and the BTRP is that they have demonstrated the value of well-coordinated, centralized research- and data-collection programs. A wide array of research initiatives have been implemented with unprecedented levels of collaboration among CPCs and important insights have been gained into meeting the logistical challenges posed by what is arguably the world’s most geopolitically complex regional fisheries management organization. Nevertheless, as of this writing, few CPCs collect adequate size, age and other biological information for ABFT and funding for research can be unpredictable.Priority should be placed on developing mechanisms to consistently fund routine data collection and research activities on a long-term basis (Polachek et al. in press).

3.2 Charting the Course for Better Management

The key to the success of the recovery plan for bluefin tuna has been the unprecedented degree of international cooperation, in terms of both management and research. Whereas in former days the Commission developed a reputation for finding ways to work around the scientific advice (Anon. 2009c), it appears to have successfully arrested overfishing and may become the first tuna regional fisheries management organization (tRFMO) to successfully rebuild a bluefin tuna stock. Even so, the true status of both the eastern and western stocks is uncertain for the many reasons already discussed, and there remains considerable pressure to substantially increase the quota and renegotiate the allocations among ICCAT members.

Dissatisfaction with the process for developing the allocation arrangements has led a number of countries over the years to lodge objections to eastern Atlantic and Mediterranean management recommendations. Under Article VII of the ICCAT Convention, objecting parties are not legally bound by the terms of the recommendation. Libya and Morocco objected to the recommendation adopted in 1998 and set their own catch limits well above the levels allocated by ICCAT, until their concerns were eventually addressed in the 2002 recommendations. Algeria, Turkey, and Norway objected to the 2010 recommendation, the latter owing to concerns about the transparency of decision-making on allocations. Turkey has been lodging objections to eastern bluefin tuna recommendations since the mid-2000s over concerns that their allocation is unfair and not in line with their historical share. Despite its objections, Turkey voluntarily complied with its assigned allocation until the adoption of Recommendation 14-04, which substantially raised the total quota for eastern bluefin, but did not change the allocation arrangement. Turkey objected to Recommendation 14-04 and established an autonomous quota consistent with what it viewed as its historical share—a level substantially higher than its ICCAT assigned quota. If other CPCs take a similar path, improvements to the scientific advice will be of little help; the management measures adopted by ICCAT will be rendered impotent and the stock may once again be in danger of collapse. Indeed, ICCAT is at a crossroads, in terms of how it governs itself and in terms of how it uses scientific advice. The question of governance, of course, involves matters of state and is beyond the scope intended for this paper. The rest of this paper therefore focuses on the use of scientific advice, which boils down to a decision on how best to manage under uncertainty.

There is a long history of literature devoted to managing fisheries under uncertainty, with most approaches falling roughly into two main paths: (1) providing an accurate accounting of the main uncertainties through the stock-assessment process, or (2) developing management procedures that are robust to likely but unquantified sources of uncertainty. The first SCRS working groups to address the matter met in 1998 and 1999 (ICCAT 1999, Gavaris et al. 2009). They suggested a simulation framework for testing the performance of several proposed harvest-control rules (HCRs) and stressed the need for joint manager-scientist meetings to make further progress, but the meetings envisioned were never held (until very recently). In 2007, a meeting was held between representatives from all five tuna RFMOs (in Kobe, Japan), where recommendations were made to “standardize the presentation of stock assessments and to base management decisions upon the scientific advice, including the application of the precautionary approach.” Subsequent meetings of the Joint Tuna RFMOs refined this advice and adopted the so-called Kobe strategy matrix, which presents the probability that a candidate management measure (e.g., a TAC) will meet the intended management objective in a specified time frame. This and other developments effectively set the Commission and the SCRS along the first path of attempting to quantify the uncertainty, with the implicit promise that more realistic assessment models and more informative data will reduce that uncertainty and eventually allow higher catch limits (closer to the MSY).

The limited financial resources available for stock assessments and supporting activities make it challenging to fully account for all of the perceived sources of uncertainty, and it becomes necessary to conduct costbenefit analyses to determine the type of research and data collection activities that are most likely to improve the stock assessment. There are also practical concerns regarding the assessment process itself and how to balance the competing needs for thoroughness, transparency, and timeliness. The SCRS has begun to move away from relying on one or two relatively simple assessment tools like surplus production models and VPAs toward a more thorough framework built on multi-model inferences and more flexible statistical models. In principle, this more comprehensive framework can take advantage of more types of data and do a better job incorporating important uncertainties. However, it is more complex and difficult to use in a working group environment where analyses and reports are expected to be complete in just a few days. Moreover, in many cases, there are only a handful of analysts available with the necessary skills. Therefore, much of the work must be accomplished outside the working group, which can affect both timeliness and transparency. The SCRS has tried to ensure the transparency of its work by requiring software, including code and documentation, to be made available through the ICCAT software catalog. It also requires that all data used in the analyses be made available to all registered participants of the meeting. Nevertheless, the details of the assessment process can be difficult to oversee from afar and may be hard to reproduce when key analysts no longer participate. Thus, in addition to consistent mechanisms for providing the needed data, the ICCAT Commission needs to ensure that the relevant expertise is consistently available if it wants to continue along the path of using more complex models and better data.

The biggest challenge for the Kobe matrix style of providing and using scientific advice, however, lies in the ability to accurately quantify the true uncertainty—or at least to do so to the satisfaction of those who must make decisions based on it. The array of possible sources of uncertainty is formidable, necessitating complex models that require more data on a continuing basis than current resources can support. The added complexity also makes stock assessments more time consuming to conduct, which mitigates against providing timely advice. The SCRS has for many years advised the Commission that the current demand for bluefin tuna stock assessments every two or three years compromises the ability of bluefin tuna scientists to conduct the research necessary to improve the assessment, and moving to more complex assessment models exacerbates the situation because they take much longer to implement and review.

The second approach to managing under uncertainty is to develop management procedures that are robust to the main perceived sources of uncertainty. It is of course impractical to test the performance of candidate management procedures on real fisheries, but relatively easy to do so through simulations of closed-loop feedback systems, otherwise known as Management Strategy Evaluation (MSE). Ideally, an MSE can be used to identify a Management Procedure (MP) that can run for several years on autopilot, without the need for managers to agree on measures based on frequent updates of the stock assessment. MSEs can also be used for strategic proposes, for example to explore the robustness of existing or proposed elements of a management regime or to identify the benefits of a proposed scientific data collection program. The Commission for the Conservation of Southern Bluefin Tuna (CCSBT) used an MSE to develop an MP for southern bluefin tuna, and the Indian Ocean Tuna Commission (IOTC) has done the same for skipjack tuna (*Katsuwonus pelamis*). The other tRFMOs are also starting to conduct MSEs for various stocks. Kell et al. (2003), for example, used MSE to evaluate the current advice framework at ICCAT as an "implicit" MP (i.e., a set of rules for management of a resource that contains all the elements of an MP but is not run on autopilot). Several HCRs have been simulation tested for North Atlantic Albacore but not yet adopted by ICCAT because more simulation trials need to be run to ensure they are sufficiently robust (Anon. 2016).

Conducting an MSE is a long process and requires six steps: (1) identification of management objectives; (2) selection of hypotheses for the Operating Model (OM); (3) conditioning the OM based on data and knowledge, and possible weighting and rejection of hypotheses; (4) identifying candidate management strategies; (5) running the MP as a feedback control to simulate the long-term impact of management; and (6) identifying the MPs that robustly meet management objectives. The first and last steps require a continuing dialogue between managers and stakeholders. The Kobe framework has helped in this respect, as have the Kobe phase plot and matrix. However, fully addressing the effect of uncertainty on achieving management objectives requires a move toward risk management. An MSE can help make that step, especially if it helps the tRFMOs to consider social and economic as well as biological objectives. This may require expanding the objectives of ICCAT to consider a range of performance statistics, such as the variability in catch as well as its magnitude, and balancing short-term versus long-term objectives (see the performance indicators of Appendix 2 in Rec. 16-21).

Considerable investments have been made toward developing OMs that represents credible hypotheses for ABFT population and fishery dynamics, and conditioning those OMs on data from the GBYP, the BTRP, and ICCAT (Kerr et al. 2013, Kerr et al. in press, Carruthers et al. 2016, Anon. in press). A main source of uncertainty important for management is the stock structure, and so the OM is being conditioned so that the robustness of current advice based on an eastern and western stock can be evaluated, and then robust alternatives proposed and evaluated. It is hoped that the results of this work will lead the way in developing an effective management procedure that bridges the gap between timely and thorough advice for ABFT.

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Figure Captions

Figure 1: Geographic distribution of Atlantic bluefin tuna (ABFT) catches per 5°x5° and per main gears for each decade (a-f) from 1960 to 2014. The vertical black line beginning at 45°W in the North Atlantic represents the delineation of the two Atlantic bluefin tuna stocks as defined by the International Commission for the Conservation of Atlantic Tunas.

Figure 2: Evolution of the catch of the Atlantic bluefin tuna for the eastern and western stocks. Reported catch for the East Atlantic and Mediterranean (MED) from Task I data from 1950 to 2015 split (*a*) by gears and (*c*) by main geographic areas and together with unreported catch estimated by the SCRS (*grey shading*; using fishing capacity information and mean catch rates over the last decade) from 1998 to 2007 (the SCRS did not detect unreported catch using fishing capacity information since 2008) and total allowable catch (TAC) levels since 1998 (*red line*). Historical catches of western bluefin tuna (*b*) by gear type and (*d*) in comparison to TAC levels agreed on by the Commission.

Figure 3: Catch of Atlantic bluefin tuna for both West (*left panel*) and East stock (*right panel*) as well as total allowable catches (TAC; *red line*) decided by ICCAT commission. For the East stock, reported catches (*dark grey bars*) and inflated catch (*light grey bars*; corresponding to estimates of actual catch by SCRS) from 1992 to 2015. The main management regulations for each stock are presented at the top of each panel (*shaded boxes*; adapted from Fromentin et al. 2014).

Figure 4: The top four figures correspond to the updated Catch Per Unit of Effort (CPUE) time series fishery indicators for the East Atlantic and Mediterranean (MED) bluefin tuna stock. All CPUE series are standardized series except the nominal Norway purse seine (PS) index. The Spanish (SP) bait boat (BB) series (*top left panel*) was split in three series to account for changes in selectivity patterns, and the latest series in 2014 was updated using French BB data owing to the sale of the quota by the Spanish fleet. The Japanese longline (LL) CPUE for the Northeast Atlantic has been updated until 2015. The Moroccan (MO)-Spanish trap CPUE was not updated. The Moroccan CPUE up to 2013 was used only for the sensitivity analysis in the 2014 stock assessment, and has been updated up to 2015. The bottom four figures correspond to the updated indices of abundance for western bluefin tuna. The dashed portions of the larval survey, U.S. Gulf of Mexico indices, and Canada Gulf of St. Lawrence indices bridge the gaps between years where data were missing or otherwise considered unreliable by the SCRS. The two Canadian indices have not been updated since 2014.

Figure 5: Recruitment scenario derived from the 2014 stock assessment. The low-recruitment-potential scenario (2-line) implies future recruitment will remain near present levels even if stock size increases. The high-recruitment-potential scenario (Beverton-Holt) implies future recruitment increases with stock size and has the potential to achieve levels that occurred in the early 1970s. Points represent the estimates from the 2014 base assessment, with the 2002, 2003, and recent year class estimates (2008-2010) highlighted. The two vertical lines represent spawning stock biomass (SSB) estimates from the 2014 assessment for 2011 (*left*) and 2013 (*right*). The inset graph shows the corresponding relationships estimated for the 2012 (*dashed lines*) and 2014 (*solid lines*) assessments, illustrating the difference in the estimated stock recruitment relationship between 2012 and 2014. VPA, virtual population analysis.

Figure 6: Median estimates of spawning biomass (age 9+), fishing mortality on spawners, apical fishing mortality (F on the most vulnerable age class), and recruitment for the base virtual population analysis (VPA) model from the 2014 stock assessment. The 80% confidence intervals are indicated with dotted lines. The recruitment estimates for the last three years of the VPA are considered unreliable and have been replaced by the median levels corresponding to the low-recruitment scenario.

Figure 7: Estimated status of stock relative to the Convention objectives (maximum sustainable yield, MSY) by year (1973 to 2013) and recruitment scenario based on the 2014 stock assessment (light blue = high recruitment potential, dark blue = low recruitment potential). The light gray dots represent the status estimated for 2013 under the low-recruitment scenario, corresponding to bootstrap estimates of uncertainty. The dark blue lines give the historical point estimates for the low recruitment, and the light blue gives the historic trend for the high recruitment.

Figure 8: Fishing mortality (for ages 2-5 and 10+), spawning stock biomass (in metric ton) and recruitment (in number of fish) estimates from virtual population analysis (VPA) continuity run from the 2014 stock assessment (considered as the base case). Red line, reported catch; blue line, inflated (from 1998 to 2007) catch.

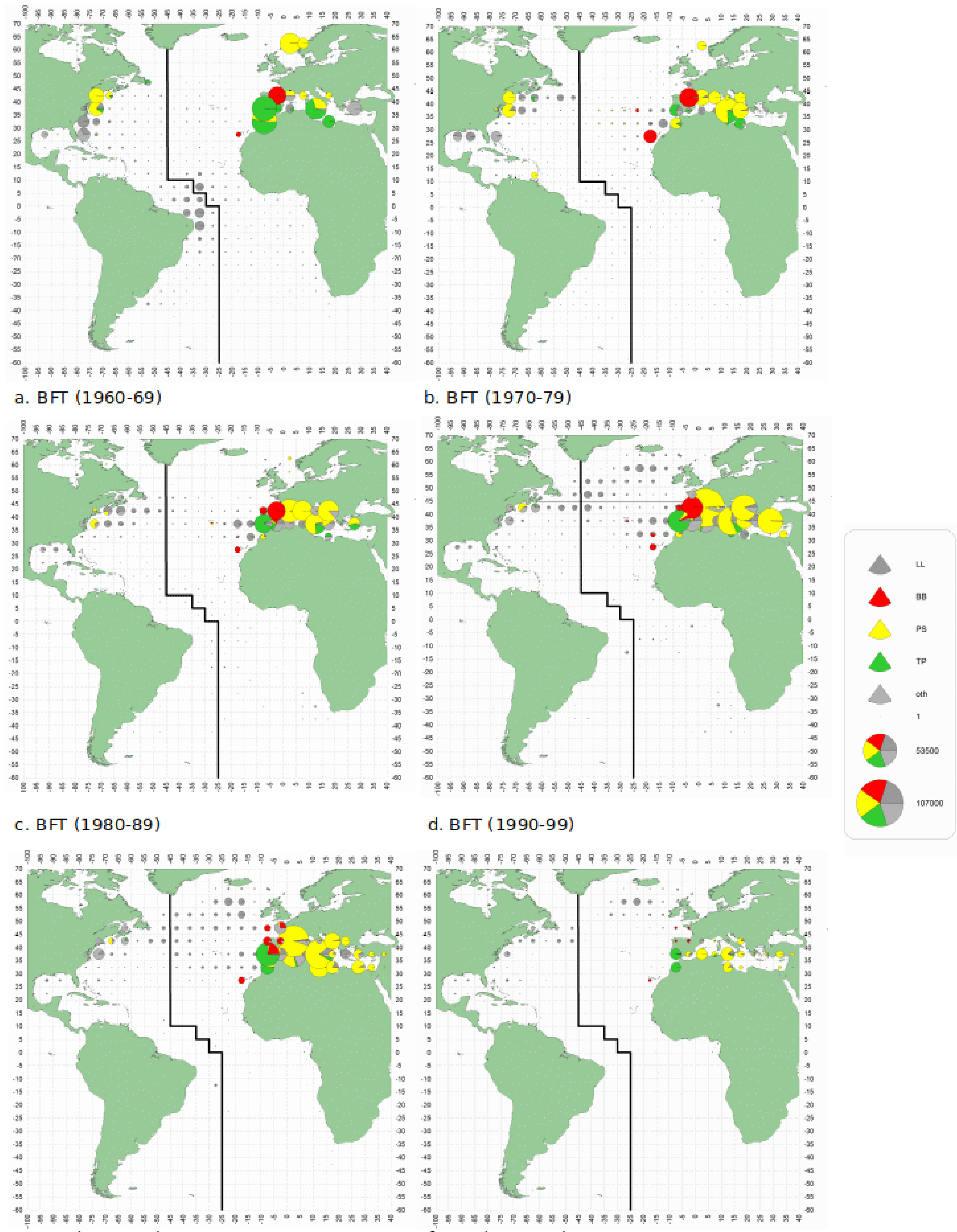
Figure 9: Stock status from 2011 to the terminal year (2013) (*black dots*) estimated from virtual population analysis (VPA) continuity run from the 2014 stock assessment with reported and inflated catch (*upper and lower panels*) and considering low, medium, and high recruitment levels (*blue*, *green*, *and red lines*). Blue, green, and red dots represent the distribution of the terminal year obtained through bootstrapping for the corresponding three recruitment levels. 2013 spawning stock biomass (SSB) and F relative to reference points calculated with the selectivity pattern over 2007-2009, which was same period as the 2010 stock assessment (*left panel*). 2013 SSB and F relative to the reference points with the selectivity pattern over 2009-2011, which was same period as the 2012 stock assessment (*right panel*).

Table Captions

Table 1: Kobe II matrices for western bluefin tuna (based on 2016 updated projections) giving the joint probability that the fishing mortality rate will be less than the level that will produce MSY (F<FMSY) and the spawning stock biomass (SSB) will exceed the level that will produce MSY (B>BMSY) in any given year for various constant catch levels under the low-recruitment and high-recruitment scenarios. The current total allowable catch (TAC) of 2,000 t (Rec. 14-05) is indicated in bold. Catch for 2016 is assumed to be 2000 t in all scenarios. MSY, maximum sustainable yield.

Table 2: Kobe II matrix for eastern bluefin tuna giving the probabilities of F<FMSY and SSB >SSBMSY for quotas from 0 to 30,000 t for 2017 through 2022 (based on 2016 updated projections). Shading corresponds to the probabilities of being in the ranges of 50-59%, 60-69%, 70-79%, 80-89% and greater or equal to 90%. The highlighted value corresponds to the 2016 total allowable catch (TAC). Catch for 2016 is assumed to be equal to the 2016 TAC in all scenarios. MSY, maximum sustainable yield; SSB, spawning stock biomass.

Figures



a. BFT (1960-69)

b. BFT (1970-79)

c. BFT (1980-89)

d. BFT (1990-99)

e. BFT (2000-09)

f. BFT (2010-14)

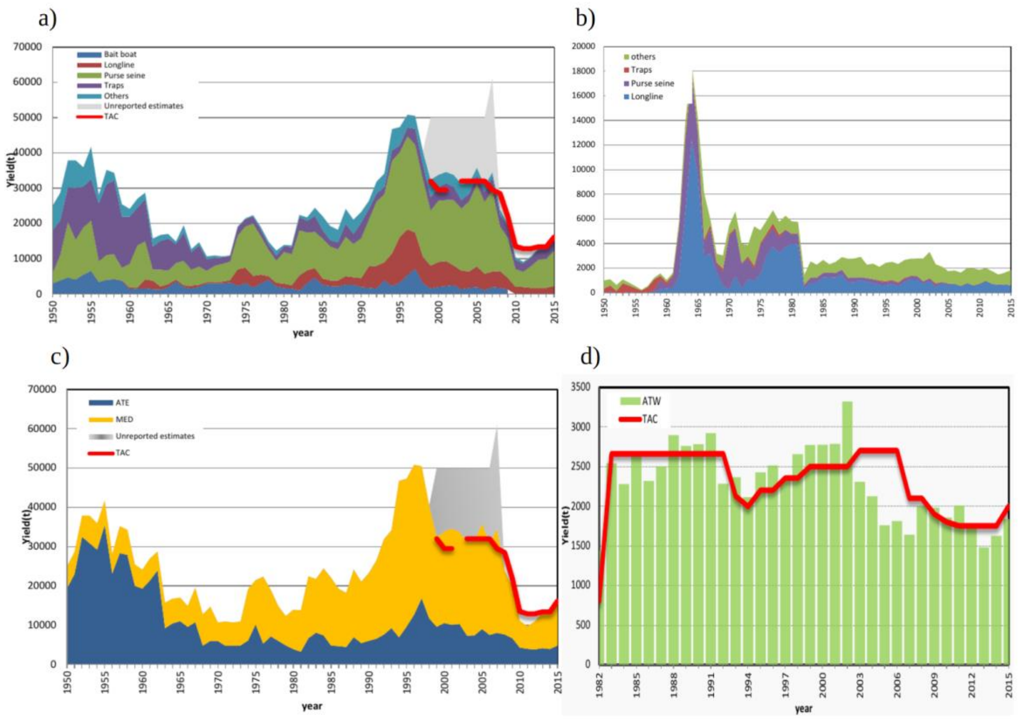


Figure 2: Evolution of the catch of the Atlantic bluefin tuna for the eastern and western stocks. Reported catch for the East Atlantic and Mediterranean (MED) from Task I data from 1950 to 2015 split (*a*) by gears and (*c*) main geographic areas together with unreported catch estimated by the SCRS (*grey shading*; using fishing capacity information and mean catch rates over the last decade) from 1998 to 2007 (the SCRS did not detect unreported catch using fishing capacity information since 2008) and total allowable catch (TAC) levels since 1998 (*red line*). Historical catches of bluefin tuna in the Atlantic West (ATW) (*b*) by gear type and (*d*) in comparison to TAC levels agreed on by the Commission.

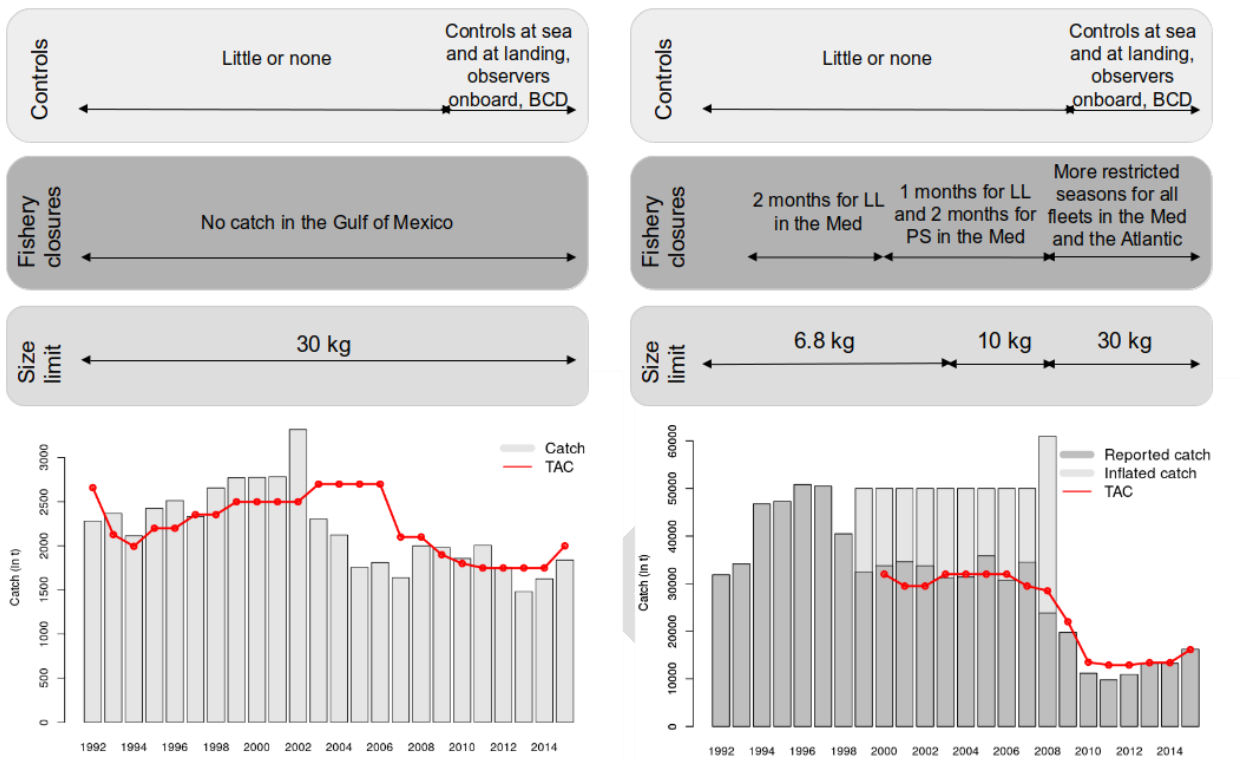
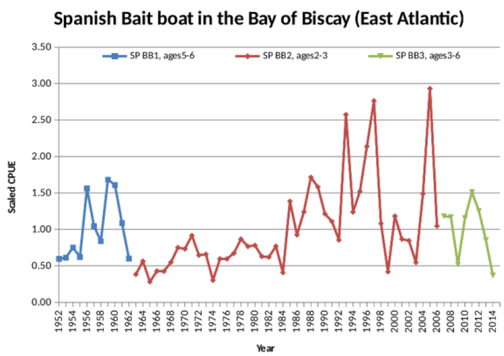
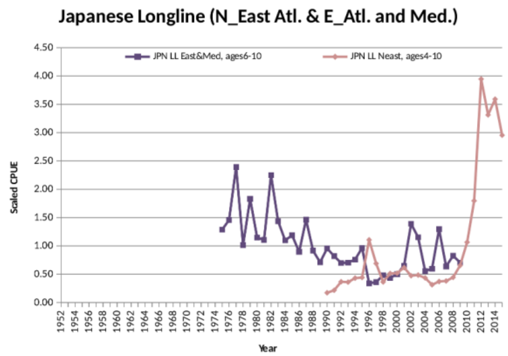
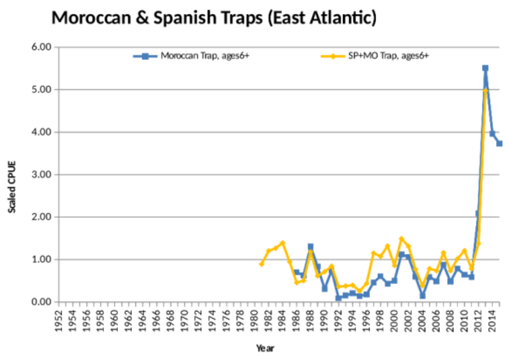
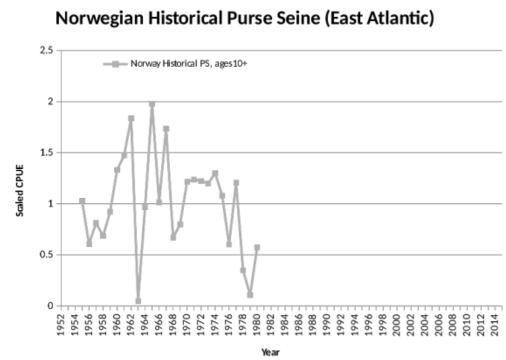


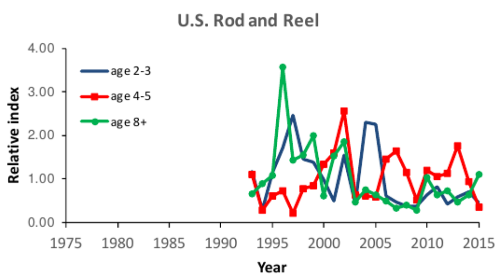
Figure 3: Catch of Atlantic bluefin tuna for both West (*left panel*) and East stock (*right panel*) as well as total allowable aatches (TAC; *red line*) decided by ICCAT commission. For the East stock, both reported catches (*dark grey bars*) and inflated catch (*light grey bars*; corresponding to estimates of actual catch by SCRS) from 1992 to 2015. The main management regulations for each stock are presented at the top of each panel (*shaded boxes*; adapted from Fromentin et al. 2014). LL, longline; MED, Mediterranean; PS, purse seine; Bluefin Catch Document,

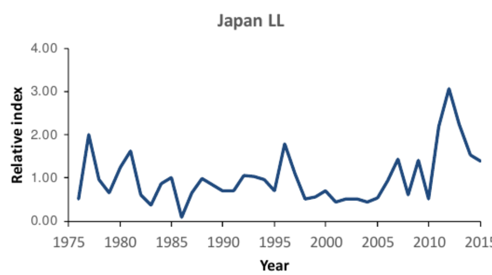

Spanish Bait boat in the Bay of Biscay (East Atlantic)
SP BB1, ages5-6
SP BB2, ages2-3
SP BB3, ages3-6
Scaled CPUE
Year

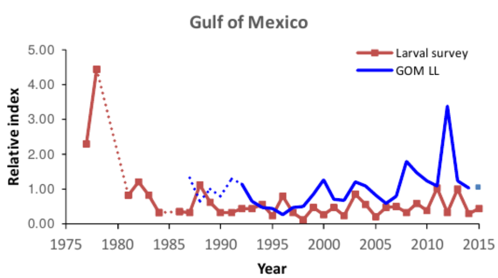

Japanese Longline (N_East Atl. & E_Atl. and Med.)
JPN LL East&Med, ages6-10
JPN LL Neast, ages4-10
Scaled CPUE
Year

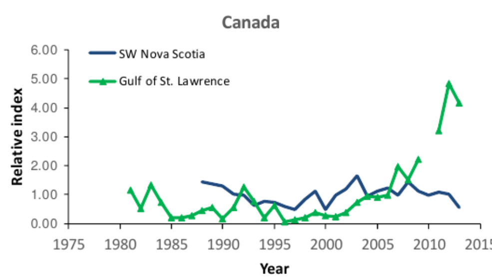

Moroccan & Spanish Traps (East Atlantic)
Moroccan Trap, ages6+
SP+MO Trap, ages6+
Scaled CPUE
Year

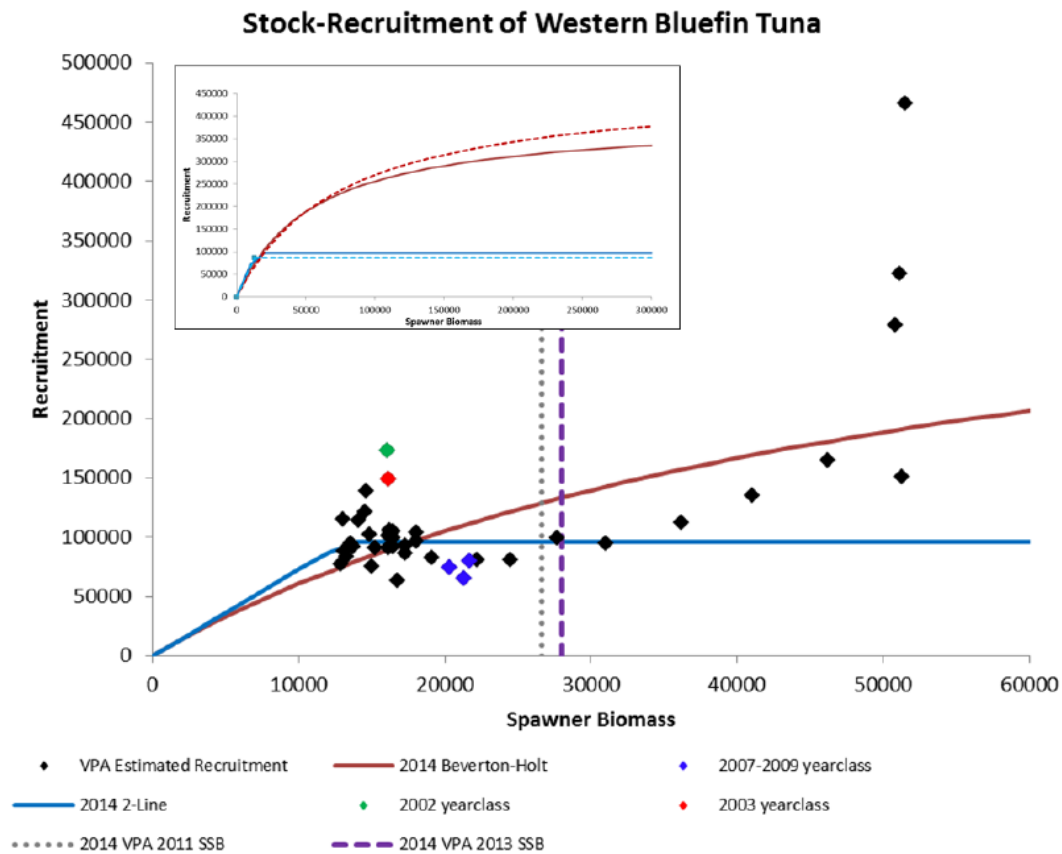

Norwegian Historical Purse Seine (East Atlantic)
Norway Historical PS, ages10+
Scaled CPUE
Year


U.S. Rod and Reel
age 2-3
age 4-5
age 8+
Relative index
Year


Japan LL
Relative index
Year


Gulf of Mexico
Larval survey
GOM LL
Relative index
Year


Canada
SW Nova Scotia
Gulf of St. Lawrence
Relative index
Year


Stock-Recruitment of Western Bluefin Tuna
Recruitment
Spawner Biomass
VPA Estimated Recruitment
2014 Beverton-Holt
2007-2009 yearclass
2014 2-Line
2002 yearclass
2003 yearclass
2014 VPA 2011 SSB
2014 VPA 2013 SSB

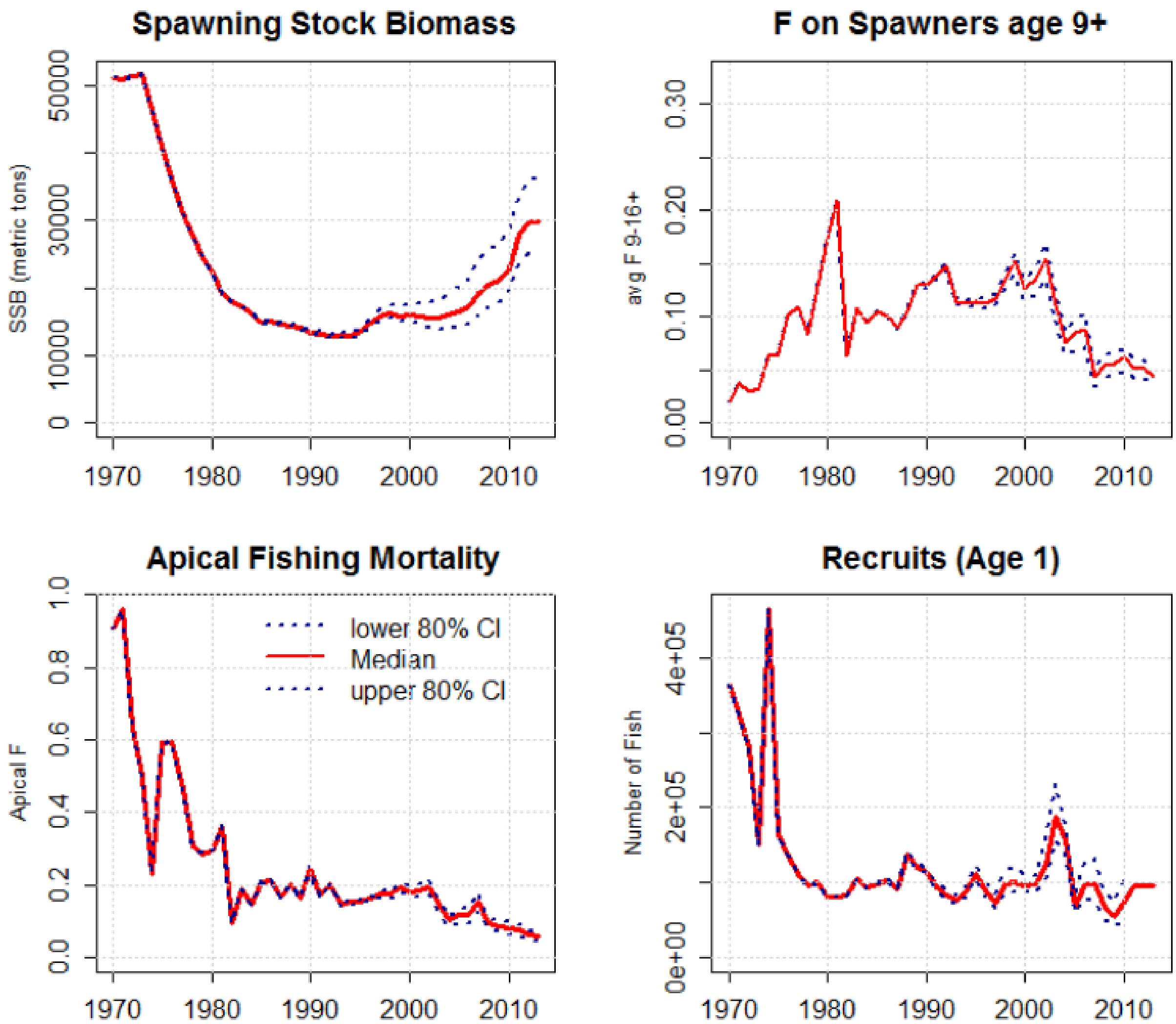


Figure 6: Median estimates of spawning biomass (age 9+), fishing mortality on spawners, apical fishing mortality (F on the most vulnerable age class), and recruitment for the base virtual population analysis (VPA) model from the 2014 stock assessment. The 80% confidence intervals are indicated with dotted lines. The recruitment estimates for the last three years of the VPA are considered unreliable and have been replaced by the median levels corresponding to the low-recruitment scenario.

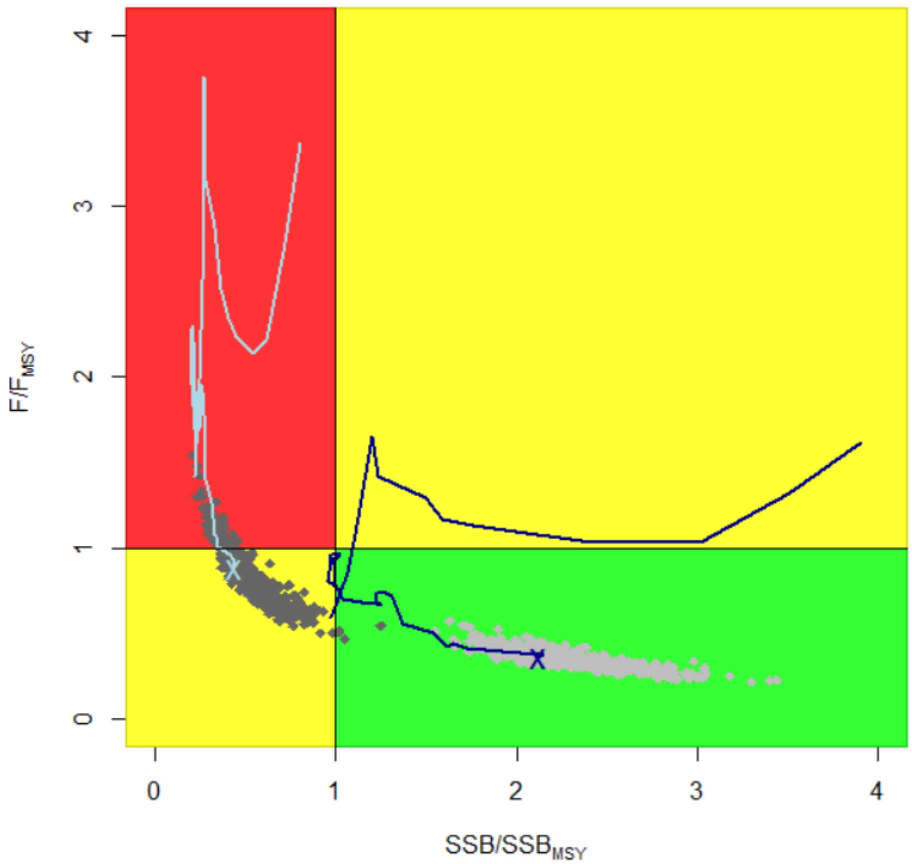


Figure 7: Estimated status of western stock relative to the Convention objectives (maximum sustainable yield, MSY) by year (1973 to 2013) and recruitment scenario based on the 2014 stock assessment (light blue = high recruitment potential, dark blue = low recruitment potential). The light gray dots represent the status estimated for 2013 under the low-recruitment scenario, corresponding to bootstrap estimates of uncertainty. The dark blue lines give the historical point estimates for the low recruitment, and the light blue gives the historic trend for the high recruitment.

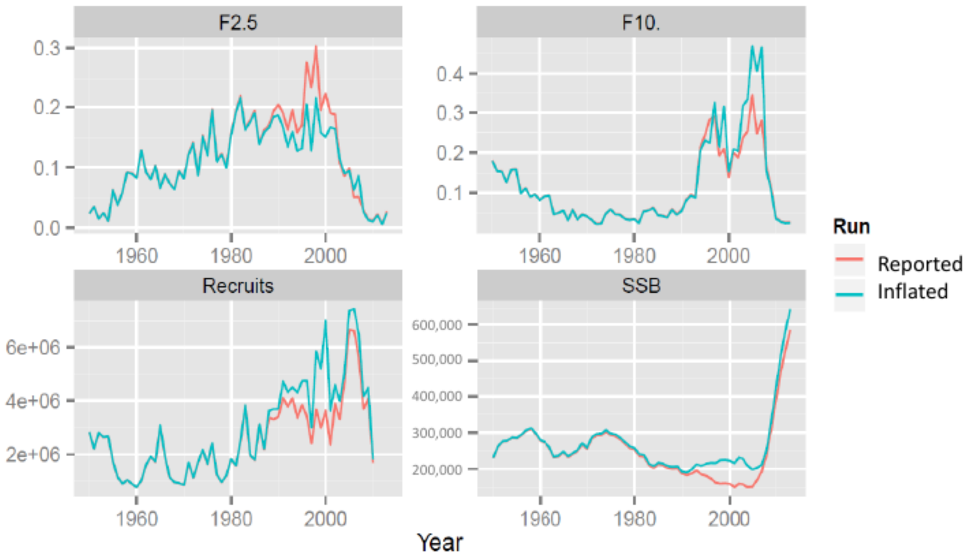


Figure 8: Fishing mortality (for ages 2-5 and 10+), spawning stock biomass (in metric ton), and recruitment (in number of fish) estimates from virtual population analysis (VPA) continuity run from the 2014 stock assessment (considered as the base case). Red line, reported catch; blue line, inflated (from 1998 to 2007) catch.

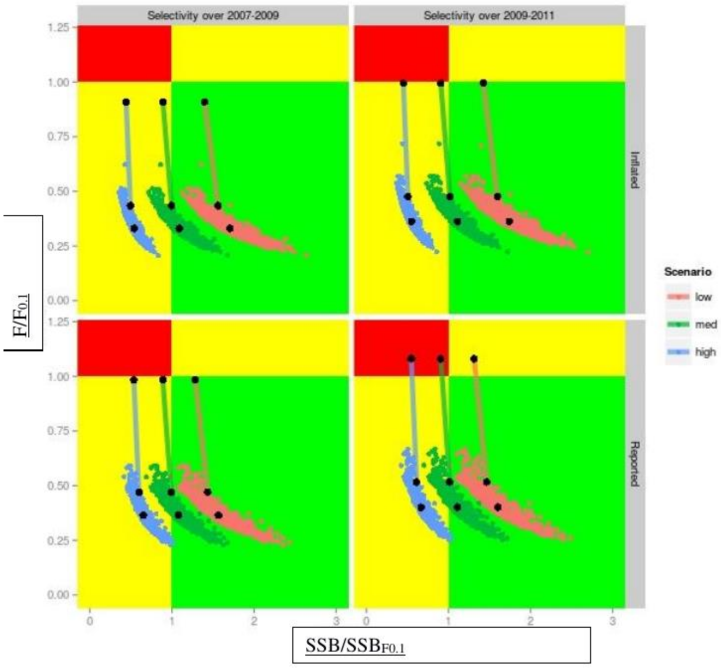


Figure 9: Stock status in the eastern Atlantic and Mediterranean Sea from 2011 to the terminal year (2013) (*black dots*) estimated from virtual population analysis (VPA) continuity run from the 2014 stock assessment with reported and inflated catch (*upper and lower panels*) and considering low, medium, and high recruitment levels (*blue, green, and red lines*). Blue, green, and red dots represent the distribution of the terminal year obtained through bootstrapping for the corresponding three recruitment levels. 2013 spawning stock biomass (SSB) and F relative to reference points calculated with the selectivity pattern over 2007-2009, which was same period as the 2010 stock assessment (*left panel*). 2013 SSB and F relative to the reference points with the selectivity pattern over 2009-2011, which was same period as the 2012 stock assessment (*right panel*).

Tables

Low Recruitment

TAC	2017	2018	2019
0 mt	100.0%	100.0%	100.0%
1500 mt	100.0%	100.0%	100.0%
1700 mt	100.0%	100.0%	100.0%
1750 mt	100.0%	100.0%	100.0%
1800 mt	100.0%	100.0%	100.0%
2000 mt	**100.0%**	**100.0%**	**100.0%**
2250 mt	100.0%	100.0%	100.0%
2500 mt	100.0%	100.0%	100.0%
2750 mt	100.0%	100.0%	100.0%
3000 mt	100.0%	100.0%	100.0%
3250 mt	100.0%	99.8%	99.6%
3500 mt	99.8%	99.4%	98.6%

High Recruitment

TAC	2017	2018	2019
0 mt	1.2%	1.2%	2.4%
1500 mt	1.0%	1.2%	1.6%
1700 mt	1.0%	1.2%	1.6%
1750 mt	1.0%	1.2%	1.6%
1800 mt	1.0%	1.2%	1.6%
2000 mt	**1.0%**	**1.2%**	**1.4%**
2250 mt	1.0%	1.0%	1.4%
2500 mt	1.0%	1.0%	1.2%
2750 mt	1.0%	0.4%	1.2%
3000 mt	1.0%	0.4%	1.2%
3250 mt	1.0%	0.4%	1.2%
3500 mt	0.8%	0.4%	1.2%

TAC	2017	2018	2019	2020	2021	2022
0 mt	77.0%	84.0%	91.0%	96.0%	98.0%	100.0%
2000 mt	76.0%	84.0%	91.0%	96.0%	98.0%	99.0%
4000 mt	76.0%	84.0%	91.0%	95.0%	98.0%	99.0%
6000 mt	76.0%	83.0%	90.0%	95.0%	98.0%	99.0%
8000 mt	76.0%	83.0%	90.0%	94.0%	98.0%	99.0%
10000 mt	76.0%	83.0%	90.0%	94.0%	97.0%	99.0%
12000 mt	76.0%	83.0%	89.0%	94.0%	97.0%	99.0%
14000 mt	76.0%	82.0%	89.0%	93.0%	97.0%	98.0%
16000 mt	76.0%	82.0%	89.0%	93.0%	96.0%	98.0%
18000 mt	76.0%	82.0%	88.0%	93.0%	96.0%	98.0%
19296 mt	**76.0%**	**82.0%**	**88.0%**	**93.0%**	**96.0%**	**98.0%**
20000 mt	76.0%	82.0%	88.0%	92.0%	95.0%	98.0%
22000 mt	76.0%	81.0%	87.0%	92.0%	95.0%	97.0%
24000 mt	76.0%	81.0%	87.0%	92.0%	95.0%	97.0%
26000 mt	75.0%	81.0%	87.0%	91.0%	94.0%	97.0%
28000 mt	75.0%	81.0%	86.0%	90.0%	94.0%	96.0%
30000 mt	75.0%	80.0%	86.0%	90.0%	93.0%	96.0%