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Challenges in the Assessment and Management of Highly Migratory Bycatch Species: A Case Study of the Atlantic Marlins

Patrick D. Lynch*, John E. Graves, and Robert J. Latour
Virginia Institute of Marine Science, College of William & Mary
Post Office Box 1346, Gloucester Point, Virginia 23062, USA

Introduction

In marine ecosystems, highly migratory species (HMS) are characterized as having vast geographical distributions, with extensive individual migrations often spanning entire oceans. Dispersal on this scale can promote ocean-wide population connectivity, resulting in many HMS exhibiting genetic homogeneity. From a biological perspective, these species often comprise a single unit stock within an ocean basin. Since single stocks can be distributed throughout multinational and international waters (as with the tunas [Family Scombridae]), sustainable management of these harvested stocks requires cooperation between all fishing nations. An international governing organization is imperative to ensure cooperation, and in the Atlantic Ocean, the member nations of the International Commission for the Conservation of Atlantic Tunas (ICCAT) are responsible for management of highly migratory fishes. The main objective of ICCAT is to maintain stocks at levels that produce maximum sustainable yield (MSY) (ICCAT 2007a), a goal that is likely shared among most fishing nations. However, numerous HMS exhibit spatial and temporal overlap, which creates management challenges since large quantities of nontarget HMS are often caught incidentally. The various HMS captured may not have the same intrinsic population growth rates or carrying capacities; therefore, their populations may not exhibit the same responses to a given level of fishing effort. Since fishers often seek productive stocks, nontarget species may be depleted at a rate faster than target species, thus sustainable management of all stocks may require a reduction of effort well below that which maximizes yield of the target species. For many fishing nations, this can result in substantial declines in commercial revenues. Since the overall importance of nontarget species inevitably varies between stakeholders, the international cooperation that is essential for management of HMS may break down when incidental catch is considered.

Numerous HMS and other large marine organisms are susceptible to incidental capture, including sea turtles (Family Cheloniidae), marine mammals (Order Cetacea), sharks (Superorder Euselachii), and billfishes (Family Istiophoridae). In the Atlantic, these species are most frequently encountered by fisheries that target tunas, swordfish *Xiphias gladius*, and sharks, with gears such as pelagic longlines, shark bottom longlines, and shark gill nets (NMFS 2007). For marine mammals, public disapproval of incidental fishing-induced mortality has been a powerful force in driving regulations (e.g., the Marine Mammal Protection Act of 1972 by the U.S. Congress) and adoption

* Corresponding author: pdlynch@vims.edu

of new technologies that have reduced their respective fishing mortalities (Hall 1998; Hall et al. 2000). However, despite historically persistent overfishing (Restrepo et al. 2003), the excessive exploitation of Atlantic billfishes, such as blue marlin *Makaira nigricans* and white marlin *Kajikia albida*, has not invoked a similar reaction (Webster 2006). While the most recent regulations imposed by ICCAT for reducing Atlantic marlin mortality are surprisingly restrictive (see Governance section, this chapter), especially when considering ICCAT's goal of maximizing yield, it is uncertain that they are capable of rebuilding the stocks (ICCAT 2006; Webster 2006). Many of the challenges surrounding management of marlins are related to uncertainties in biological and fisheries data, resulting in uncertainties in the assessment process (Restrepo et al. 2003; Die 2006). Here, the focus is on Atlantic marlin populations and potential quantitative approaches to reduce uncertainty in their assessments, thereby promoting international cooperation and the implementation of sustainable management measures.

Importance

Globally, istiophorids comprise five genera and nine species (Collette et al. 2006). Of these, six species occur regularly in the Atlantic Ocean and its adjoining seas: blue marlin, white marlin, sailfish *Istiophorus platypterus*, longbill spearfish *Tetrapturus pfluegeri*, Mediterranean spearfish *T. belone*, and roundscale spearfish *T. georgii*. Blue marlin and white marlin are distributed throughout tropical and temperate waters of the Atlantic, ranging from Canada east to the Azores in the northern hemisphere to Argentina east to South Africa in the southern hemisphere (Figure 1). There is a temporal trend to their distribution, with presence in the higher latitudes typically occurring during warmer times of the year. Atlantic marlins tend to exhibit solitary behavior; however, small aggregations of white marlin have been observed (Nakamura 1985). As with all istiophorids, the marlins likely exhibit extremely rapid growth rates in early life (Sponaugle et al. 2005), but the average size of an adult blue marlin (100–175 kg) is much larger than that of a white marlin (20–30 kg) (NMFS 2007). Also, sexually dimorphic growth is common to both species (though much more pronounced in blue marlin), with females growing larger than males (Nakamura 1985; Wilson et al. 1991; Arocha and Bárrios 2009).

Marlins are apex piscivores that also consume invertebrates such as squid (de Sylva and Davis 1963; Nakamura 1985; Cox et al. 2002a; Júnior et al. 2004; Shimose et al. 2006). Apex predators are often considered ecologically important, as their depletion may impact food web structure through a trophic cascade (Paine 1969; Pace et al. 1999; Casini et al. 2009). However, Kitchell et al. (1999) demonstrated that the simulated removal of billfishes from the central North Pacific ecosystem had a minimal impact on trophic structure. In fact, in an assessment of importance, Kitchell et al. (2006) stated that the economic value generated by billfish angling is far greater than their ecological value as apex predators. While the uncertainty associated with complex ecosystem models such as these can be overwhelming, it may be that healthy Atlantic marlin populations are not critical to maintaining ecosystem stability; however, it is certain that their sustainability is of significant economic importance for artisanal communities and countries with recreational fisheries.

Since its beginning in the late 1800s to early 1900s, the recreational billfish fishery has been an important component of the tourist industry in many parts of the world (Holder 1912; Jordan and Evermann 1923). Though difficult to calculate on a global scale, Ditton and Stoll (2003) estimated

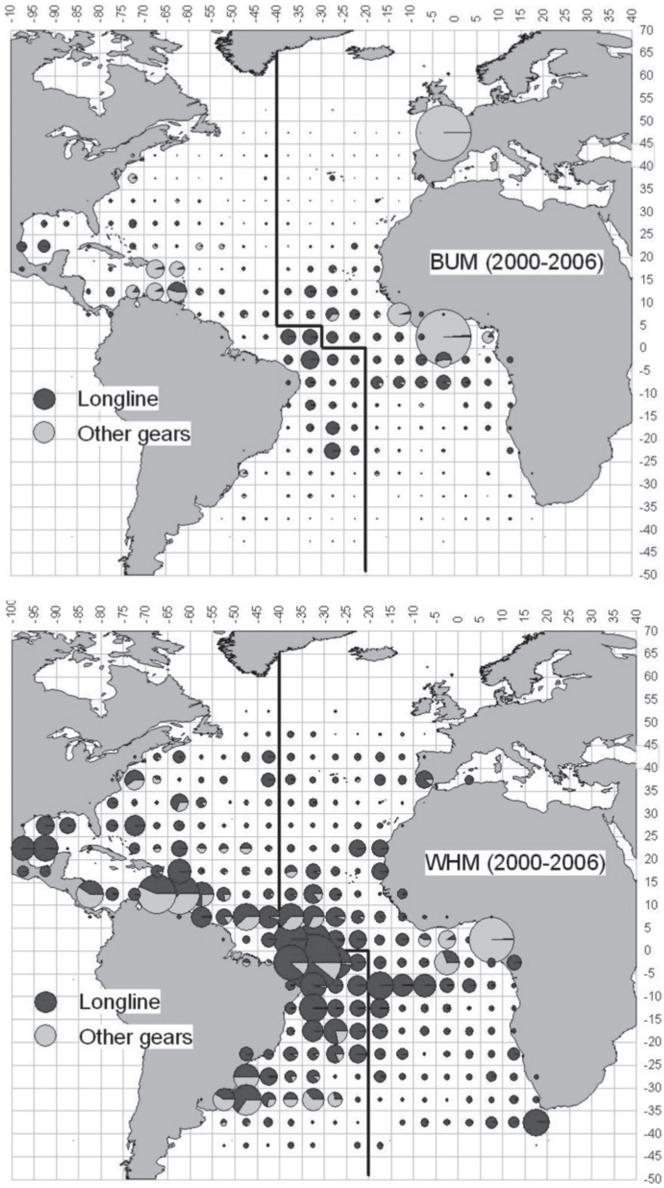

Figure 1. Distributions of blue marlin (BUM) and white marlin (WHM) in the Atlantic Ocean as determined from fisheries catch data from 2000 to 2006. The largest circles for BUM and WHM correspond to catches of 789 and 52 metric tons, respectively. Source: ICCAT (2009).

the economic impact of this fishery (for several countries combined) to be between US$203.95 million and $339.91 million, annually. Additionally, the economic importance of recreational billfish fisheries is emphasized by the regulatory actions of the United States. To reserve billfish for recreational fishing, commercial retention of Atlantic marlins has been prohibited in the United States since implementation of the 1988 Fishery Management Plan for Atlantic Billfish. Also, by law, the United States mandates a recreational fishing presence in the policy-making process by declaring that at least one of the U.S. commissioners to ICCAT must possess "knowledge and experience regarding recreational fishing in the Atlantic Ocean, Gulf of Mexico, or Caribbean Sea" (U.S. Congress 1975). This presence is critical to marlin recreational fisheries, as the interests of billfish anglers often differ from those of commercial fishers that target HMS.

In addition to the significant economic contributions, marlin recreational fisheries are also valued for their social and historical importance. In the mid-20th century, writers such as Zane Gray and Ernest Hemingway romanticized big game fishing, prompting a rapid increase in the popularity of angling for marlins (Peel et al. 2003). This popularity continues today, but the recreational fishing community has recognized that sustainability of marlin populations is imperative to preservation of their fishery. Thus, to minimize fishing mortality, recreational marlin fisheries have become primarily catch and release. An appreciable percentage of marlins will likely survive this practice, but the rate of postrelease mortality may vary depending on fishing gear and other fishing characteristics (Serafy et al. 2009). While catch-and-release fishing began to take hold following years of substantial recreational landings, it does not represent a considerable sacrifice for most fishermen; it is the challenging fight that precedes capture rather than the capture itself that has drawn many people to the sport (Ditton and Stoll 2003).

Commercially, marlins are of lesser importance than many other HMS. They are landed as nontarget bycatch of fisheries that target tunas and swordfish because the amount of biomass landed and their value per kilogram are lower than these target species. While current ICCAT regulations require the release of any marlin caught alive (ICCAT 2007b, Rec. 2006–09), longline operations often land fish that are dead upon retrieval of the gear. These harvests represent the largest source of fishing mortality for the Atlantic marlins, with Brazil, Japan, and Chinese Taipei constituting the bulk of the landings (ICCAT 2006).

Following peaks in the 1960s, total marlin landings have fluctuated over time with decreasing trends exhibited in recent years (Figure 2). Historical oscillations in total landings essentially tracked longline effort (Restrepo et al. 2003). While recent declines in reported landings may be a result of live release from longline operations, further reduction of fishing mortality could be achieved through a decrease in overall effort or changes in fishing practices. However, given the potential resulting loss of target catch, either of these approaches would likely face substantial resistance by any ICCAT member nation that places a low value on recreational fisheries for marlins.

On a smaller scale, directed artisanal fisheries for Atlantic marlins are conducted by coastal nations, especially in the Caribbean Sea and off the coast of western Africa (ICCAT 2001a). These subsistence fisheries represent the only real reliance on marlins for their nutritional value (Peel et al. 2003). Thus, marlin stock collapses may have little impact on large commercial operations but could represent losses of valuable sources of protein for many developing coastal nations.

Another important group of stakeholders with an interest in Atlantic marlins is the environmental community. This constituency is most concerned with the existence and/or ecological values of the species. However, conservation of marlins has been a relatively low priority when considering the resources dedicated to preserving other charismatic marine megafauna such as bluefin tuna *Thunnus thynnus*, sea turtles, and marine mammals, but since recreational fishermen are also interested in healthy marlin populations, the messages and actions of the two groups are often aligned. A major exception to this collaboration occurred in 2001, however, when some conservationists petitioned to have white marlin listed as a threatened or endangered species under the U.S. Endangered Species Act (ESA; WMSRT 2002). If successful, a listing could have

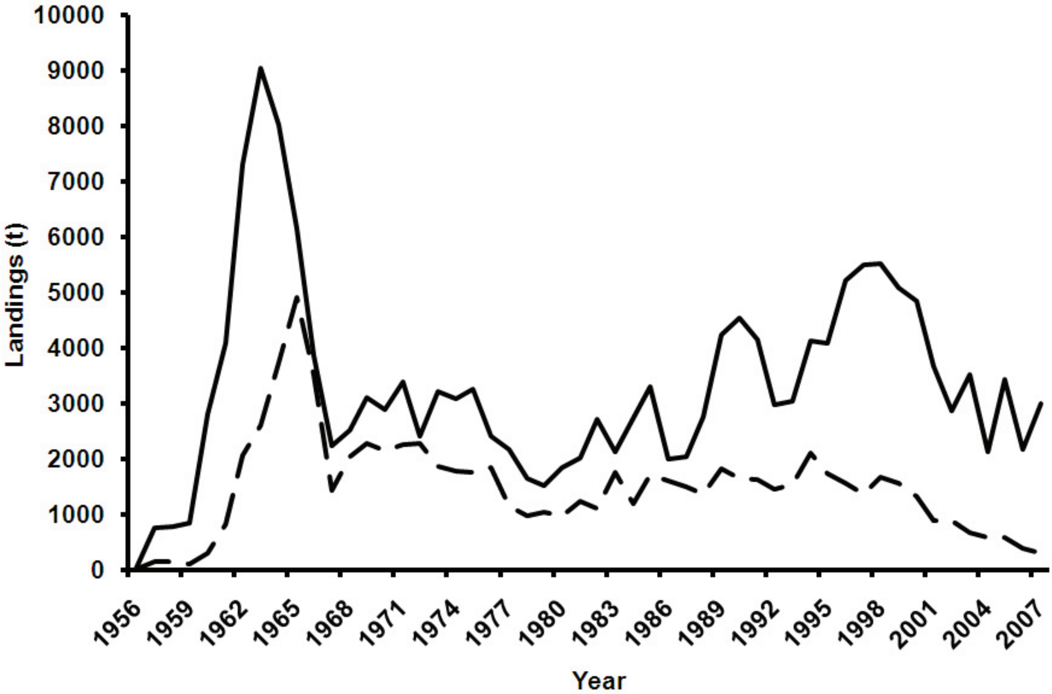

Figure 2. Total annual landings of blue marlin (solid line) and white marlin (dashed line) in the Atlantic Ocean. Data source: ICCAT online catch database (www.iccat.int/en/accesingdb.htm). t = metric tons.

significantly impacted any recreational fisheries in the United States that have the potential to interact with white marlin. In 2002, the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration determined that the petitioned action was "not warranted" despite concluding that the species was overexploited and that regulatory mechanisms implemented at that time were likely unable to prevent continued overfishing (WMSRT 2002). Subsequently, following further pressure from conservationist groups, NMFS agreed to reassess the species upon completion of the 2006 white marlin stock assessment conducted by ICCAT. After re-evaluation, NMFS maintained that the species did not warrant listing as threatened or endangered (WMBRT 2007).

Overall, the Atlantic marlins are most important to recreational and artisanal fisheries, and they are of relatively low commercial value. Their conservation hinges on an understanding of susceptibility to anthropogenic impacts, which is enhanced with knowledge regarding the sizes and distributions of marlin populations as related to habitat.

Populations and Habitats

Starting in 2000, Atlantic blue and white marlins have been considered to comprise single unit stocks for assessment and management purposes (Restrepo et al. 2003; ICCAT 2006). Prior to this, it was assumed that the populations each contained northern and southern stocks separated at 5°N (Restrepo et al. 2003). Recent genetic analyses supported the single unit stock approach for both populations (Graves and McDowell 2006; McDowell et al. 2007); however, Graves and McDowell

(2006) identified significant spatial heterogeneity for white marlin, highlighting a potential need for continued research on their stock structure.

Current scientific understandings of population dynamics and stock status for marlins are entirely fishery-dependent, that is, independent research surveys are not used to monitor their populations. Therefore, estimates of historical biomasses are based on relative measures of catch per unit of effort (CPUE) obtained from the various fisheries, which are assumed proportional to exploitable abundance. Because the fisheries do not sample the populations in a random, unbiased fashion, a complete reliance on fishery-dependent data may introduce many potential sources of error. However, CPUE time series, and assessment models fitted to CPUE data are currently the best available estimates of historical relative abundance. Despite a potentially promising trend in recent years for white marlin, the relative biomasses estimated for each species have declined substantially from 1950s levels (Figure 3). In the context of MSY, these trends do not reflect sustainable harvests, but estimated biomasses may not be accurate because CPUE can be affected by changes in fishing practices regarding target species as well as changes in marlin abundance. Efforts to account for potential biases require an understanding of the relationship between marlin habitat, susceptibility to capture, and the spatiotemporal dynamics of fishing effort (Maunder and Punt 2004; Bishop 2006).

As with the overlapping geographical distribution of Atlantic marlins, the vertical habitats utilized by these species are also similar. Valuable characterizations of vertical habitat utilization for large pelagic fishes have come from studies that used pop-up satellite archival tags (PSATs) to monitor animal behavior (Arnold and Dewar 2001; Luckhurst 2007; Hofmann and Gaines 2008). These tags record a nearly continuous stream of specified environmental parameters (temperature, pressure [depth], light, etc.), archive the data, and transmit the information via satellite after releasing from the organism and floating to the surface (Graves et al. 2002). There have been several studies in the Atlantic and adjacent seas that attached PSATs to blue marlin (Graves et al. 2002; 2003; Kerstetter et al. 2003; Saito et al. 2004; Prince et al. 2005; Luo et al. 2006; Prince and Goodyear 2006; Kraus and Rooker 2007; Goodyear et al. 2008) and white marlin (Horodysky and Graves 2005; Prince et al. 2005; Kerstetter and Graves 2006a; Horodysky et al. 2007; Graves and Horodysky 2008). The studies that made inferences about habitat utilization revealed similar trends; both species spent the majority of their time in warmer surface waters (<10 m) but made regular short-duration dives to deeper water (occasionally >100 m) (Graves et al. 2003; Kerstetter et al. 2003; Saito et al. 2004; Prince et al. 2005; Luo et al. 2006; Prince and Goodyear 2006; Horodysky et al. 2007; Kraus and Rooker 2007; Goodyear et al. 2008).

While depth can be an informative descriptor for habitat, it is more likely that sea surface temperature (SST) and relative deviations from SST govern marlin distributions through physiological pathways. Brill and Lutcavage (2001) suggested that cardiac function is compromised in billfish when they dive to cooler waters that exceed an 8°C deviation from SST. This implies that these fishes are constrained to a relative temperature-at-depth distribution. Additionally, in areas with a shallow thermocline above hypoxic water, dissolved oxygen concentrations can further limit billfish distributions (Prince and Goodyear 2006). Thus, an understanding of marlin habitat is a key component to sustainable management. When evaluating vulnerability to fishing gear, it is not enough to simply consider the depth at which fishing effort is imposed, but the physical properties of the water column must also be incorporated.

Besides fishing, there are numerous human actions that may also affect marlin abundance. A review of anthropogenic impacts on billfish by de Sylva et al. (2000) highlighted a range of

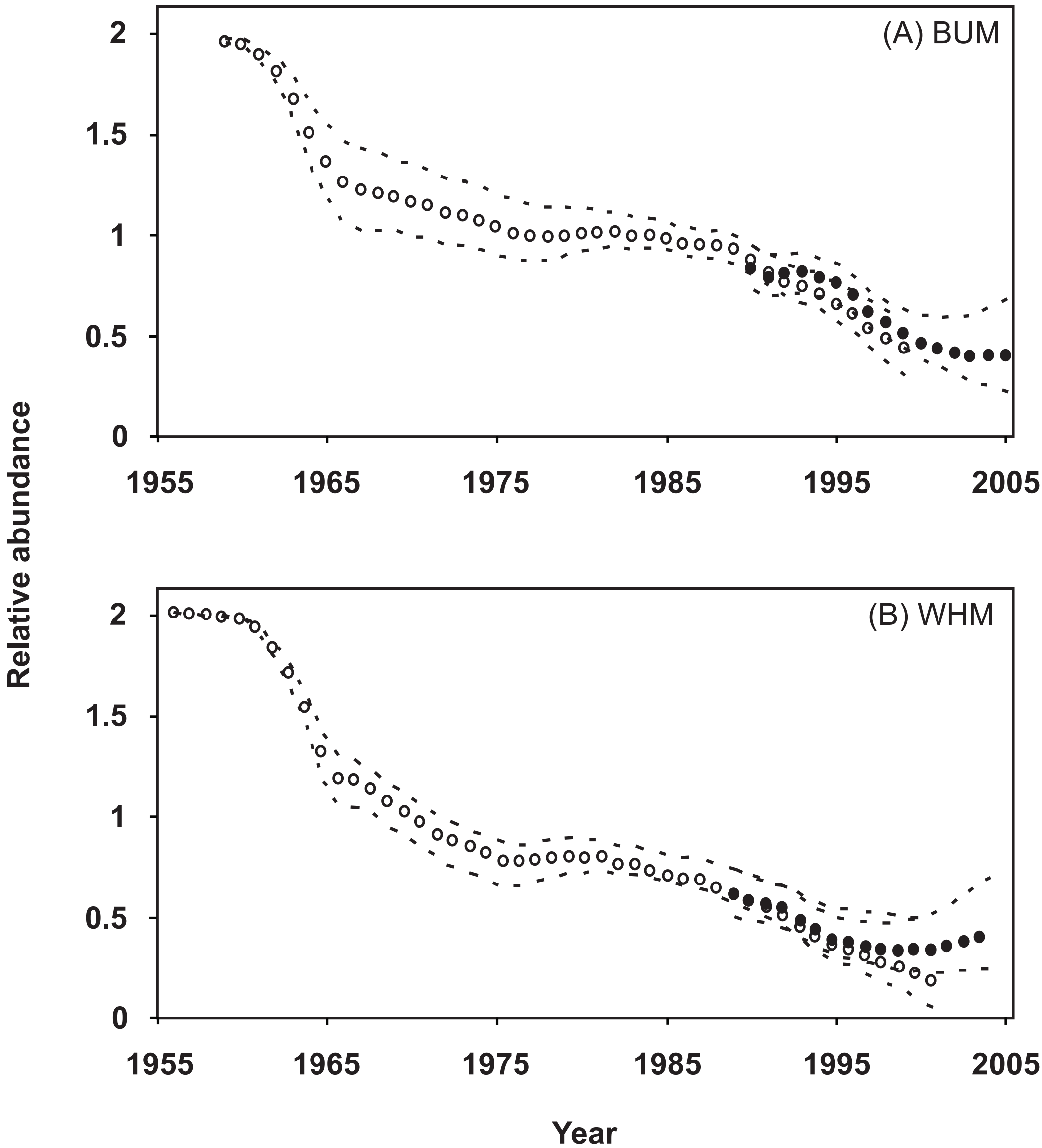

Figure 3. Estimated relative abundance of blue marlin (A: BUM) and white marlin (B: WHM), derived from production model fits to catch-per-unit-effort data from the most recent assessments (solid circles) and previous stock assessments in 2000 for BUM and 2002 for WHM (open circles). The models used in the assessments were similar, but the recent assessments were fit to all available catch-per-unit-effort time series separately, where the previous assessments considered a single composite index of abundance-Dashed lines represent 80% confidence intervals. Source: ICCAT (2007c).

potential sources, including direct (e.g., fishing) and indirect (e.g., point and nonpoint sources of pollution) impacts that may degrade marlin habitats. Since marlins are distributed throughout relatively stable environmental conditions, they may be more susceptible to subtle ecological perturbations than coastal eurytopic organisms that experience variable conditions (de Sylva et al. 2000).

Given that Atlantic marlins are exploited across vast spatial scales, delineation of their habitats and the potential impacts of habitat degradation are crucial for conservation of these species. This is especially important since historical population trajectories indicate declines in abundance, raising concerns about the future for Atlantic marlins. There may be reason for cautious optimism, however, because relative biomass estimates from the 2000s suggest that the declines may have been arrested or, in the case of white marlin, the population may be in the early stages of a recovery (Figure 3). It is possible that these responses are the direct result of management measures, but there is little certainty in the trends in biomass, and several additional years of data are required to verify population responses (ICCAT 2006).

Fisheries

Fisheries targeting HMS have operated for many years, but until the 20th century, fishing was largely constrained to coastal waters (Majkowski 2007). In the early 1900s, a growing demand for canned tuna prompted the development of industrialized fisheries, including the Japanese longline fleet. By 1932, Japan had developed factory longline ships capable of canning tuna onboard (Morgan and Staples 2006). Following the elimination of post-World War II restrictions, this fleet expanded rapidly, eventually reaching the Atlantic Ocean in the late 1950s. Initially targeting yellowfin tuna *Thunnus albacares* and albacore *T. alalunga* in surface waters, the Japanese longline fishery was almost entirely responsible for the observed peak in Atlantic marlin landings in the late 1950s to early 1960s (Figure 2). Toward the end of the 1960s, developments in cold storage technology enabled Japanese fishermen to transition from the canned tuna market to a more lucrative sashimi market. This shift prompted a change in target species from yellowfin tuna and albacore to bigeye tuna *T. obesus* and bluefin tuna. By the early 1970s, the higher-valued target species dominated the catches in the Atlantic (Sakagawa et al. 1987). Since these species utilize deeper habitats, longline practices were altered to fish deeper in the water column (Majkowski 2007). Following this change, total landings of Atlantic marlins declined quickly, then fluctuated for many years before exhibiting further declines (white marlin, in particular) throughout the past decade (Figure 2).

Despite decreases in landings and potentially stabilizing biomass trajectories, the latest stock assessments concluded that Atlantic blue and white marlin stocks remain overfished and overfishing persists (ICCAT 2006). Given that ICCAT manages with respect to MSY, "overfishing" occurs when the fishing mortality rate (F) exceeds the rate associated with maximum sustainable yield (F_{MSY}). Marlin stocks have been experiencing overfishing throughout much of the historical time series, but in recent years, F has drastically increased with respect to F_{MSY} (Figure 4). As relative biomasses have continued to decline (Figure 3), the reductions in landings necessary to rebuild the populations to MSY levels are greater than those observed. The recent changes in biomass trajectories may, in fact, be in response to management measures, but with lags in implementation and collection and reporting of data, the full effects of the measures may not be observed for several years. This delay could be detrimental to the species if the regulations prove inadequate for stimulating stock recoveries.

For many bycatch species, fishing mortality has been reduced through technological developments that attempt to improve survival of nontarget organisms while maintaining catch rates of target species. There have been relatively few developments that accomplished this for marlins; however, the use of circle hooks (as opposed to traditional J-style hooks) may show promise. In a review

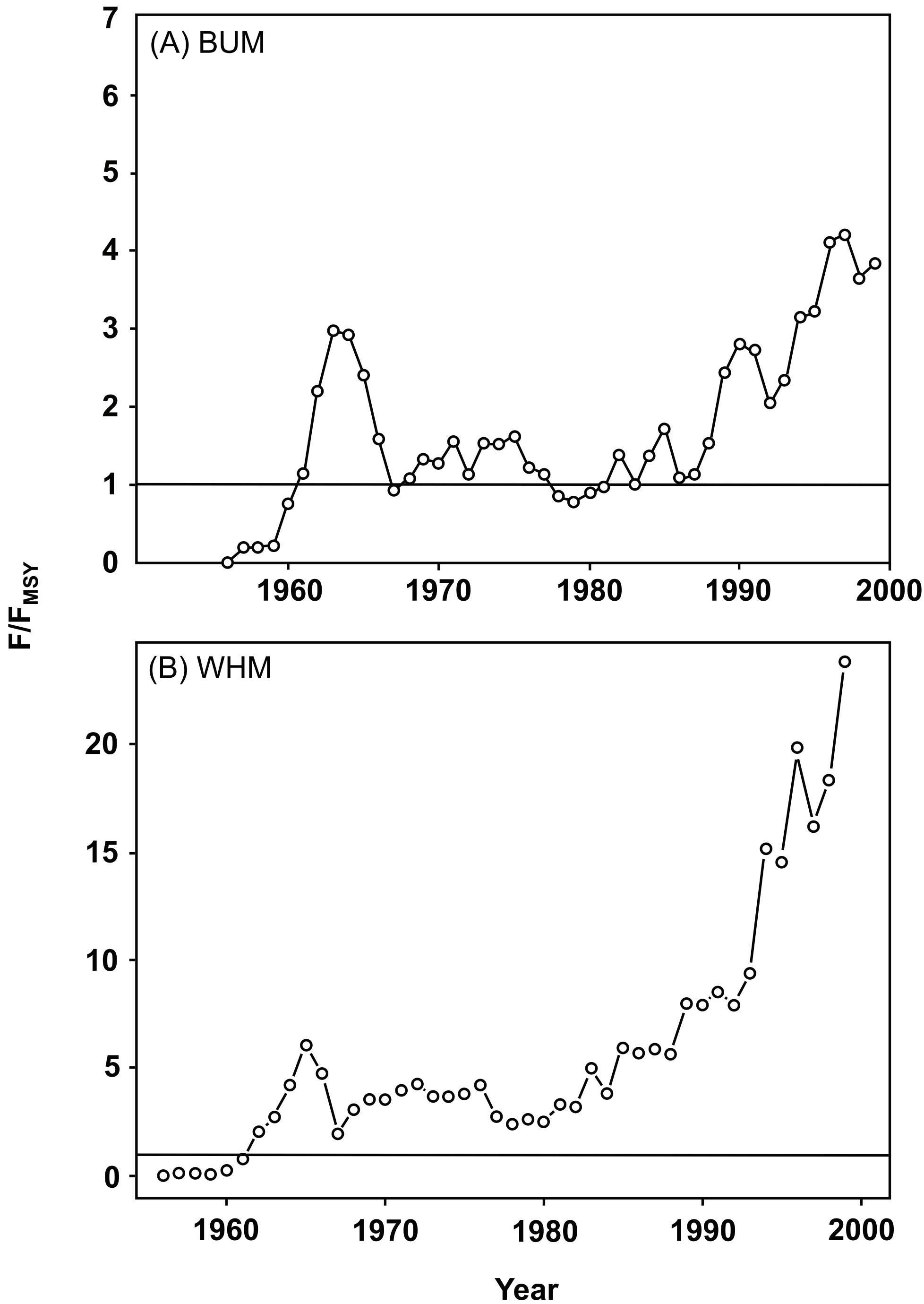

Figure 4. Historical trends in relative fishing mortality rate (F) with respect to the rate at maximum sustainable yield (F_{MSY}) for blue marlin (A: BUM) and white marlin (B: WHM) in the Atlantic Ocean. Estimates were generated in the 2000 stock assessments using a logistic production model. Points above the solid horizontal line represent years in which $F > F_{MSY}$ trajectory. Source: ICCAT (2001b).

of studies that tested the effect of hook choice on billfishes, Serafy et al. (2009) determined that circle hooks are beneficial to billfish conservation efforts, and they recommended their use in commercial pelagic longline and recreational fisheries. However, when examining hook-induced mortality rates for blue and white marlins specifically, there are conflicting results among fisheries. For instance, in recreational fisheries for white marlin, circle hooks have been shown to significantly improve postrelease survival as compared to J hooks (Horodysky and Graves 2005). Yet, for pelagic longlines, white marlin mortality was slightly higher on circle hooks, though not significantly (Kerstetter and Graves 2006b). However, for most species analyzed, mortality rates were generally higher on J hooks than on circle hooks, and catch rates of the target species were not significantly impacted. It should be noted that mortality estimates in studies that used PSATs reflected postrelease mortality after a specified number of days, while in other studies mortality was the percentage of fish that were alive when brought alongside the boat (Serafy et al. 2009). There were not enough blue marlins captured (n = 1) for Kerstetter and Graves (2006b) to test the effects of hook type on survival, and there are currently ongoing studies comparing hook types in recreational fisheries for blue marlin.

In general, when compared to J hooks, circle hooks tend to reduce incidences of deep-hooking and bleeding in billfishes (Serafy et al. 2009). Thus, in the most recent stock assessment report, it was recommended that ICCAT consider encouraging the use of circle hooks to increase the chances of rebuilding Atlantic marlin stocks (ICCAT 2006). In the United States, the use of circle hooks has been mandatory in the pelagic longline fishery following the 2004 ESA section 7 consultation. This implementation was intended to minimize impacts on sea turtles, but marlin populations may also benefit. Also, circle hooks are currently required in all U.S. recreational Atlantic billfish tournaments when natural baits are used (NMFS 2006).

Recent stock assessments suggested that current fishery removals of Atlantic marlins are at levels too high to permit rebuilding to MSY levels. As relatively low value bycatch species of commercial fisheries, further depletion of marlin populations is not likely to substantially impact future commercial interests; however, recreational and artisanal fisheries will suffer in the absence of harvest policies that promote rebuilding. These trade-offs should be considered when management formulates recommendations, since international cooperation is required to attain sustainability. However, to rebuild populations to levels that support MSY, the main focus of management must be on the outcomes of stock assessments, which are scientific analyses of the status of the populations. Unfortunately, insufficient data result in numerous uncertainties in Atlantic marlin assessments (Restrepo et al. 2003; Die 2006), leading to disagreements over interpretations of assessment results, which serve as a basis for ICCAT member nations to object to further management restrictions. In fact, Webster (2006) identified uncertainty in the stock assessment process and the resulting lack of consensus regarding stock status as major factors preventing acceptance of more conservative international management measures for Atlantic marlins. Thus, identifying and accounting for assessment uncertainties is an important step in improving the management of blue and white marlins in the Atlantic.

Assessment Uncertainties

Resource managers are faced with numerous sources of uncertainty, ranging from those analytical to those related to institutions and management (Hilborn 1987; Francis and Shotton 1997). While the consideration of management institutional uncertainties (i.e., uncertainties surrounding determination and implementation of management objectives and policies) is crucial for achieving sustainability, the focus here is on analytical uncertainties related to stock assessments and population dynamics (e.g., observation, model, and estimation uncertainty). Failure to address these sources of uncertainty can translate to errors in stock assessments, skepticism regarding stock status, and poor management advice; thus, the consideration of analytical uncertainties is an essential component of reliable sustainable resource management.

The importance of addressing analytical uncertainties in fisheries management is emphasized by the dynamics of the Atlantic herring (also known as the North Sea herring) *Clupea harengus* fishery. This stock has experienced two periods of severe overexploitation since the 1960s (Simmonds 2007). While warnings from scientists preceded the first decline, data at that time were insufficient to accurately determine stock status (i.e., observation uncertainty), and management action was resisted on this basis to preserve commercial profits. The stock eventually collapsed, moratoria were imposed, and a slow recovery followed. During the next period of overexploitation, the scientific understanding of the stock was more reliable, allowing management to take actions to successfully prevent a second total collapse. However, there were errors in the assessments during this decline, leading to an underestimation of exploitation rates. Had this not been the case, a second severe stock depletion may have been avoided altogether.

This example accentuates the importance of accounting for scientific uncertainty in fisheries management, and the lessons learned may translate to the management of many stocks, including Atlantic marlins. Similar to the tenor surrounding the initial decline in North Sea herring, Atlantic blue and white marlins are thought to be experiencing overfishing, but management measures are resisted, in part because of substantial uncertainties in the stock assessments. Delays in the enactment of management measures have been shown to increase the severity in the measures needed for stock rebuilding, the time required for rebuilding, and even the likelihood of stock collapse (Shertzer and Prager 2007). Therefore, unless the uncertainties are fully addressed and scientific advice is heeded, the management failures of the herring fishery may be repeated for Atlantic marlins.

The most recent stock assessments for Atlantic marlins were conducted by the Standing Committee for Research and Statistics (SCRS) of ICCAT in 2006. The assessments were performed using a Bayesian surplus production (BSP) model (McAllister et al. 2001; Babcock 2007) on catch data from 1990 to 2005, although catch data for 2005 were incomplete. The 2006 assessments seem to have improved scientific understandings of population dynamics in recent years; however, numerous sources of uncertainty remain.

Catch-per-Unit-of-Effort Standardization

Perhaps the most significant sources of debate and uncertainty in marlin assessments are CPUE standardization methods. The assessment models are "tuned" to CPUE time series, which represent indices of relative abundance under the assumption that catch (adjusted by effort) is proportional to abundance. However, numerous factors can impact catch that are not a result of changes in population size, including altering the temporal or spatial distribution of fishing effort, modifying fishing gear, and changing target species. If these factors are not accounted for, then the proportionality assumption is violated and CPUE no longer reflects relative abundance (Maunder and Punt 2004). This could introduce substantial error into the assessments.

There are two general approaches to standardizing marlin CPUE currently under consideration. The method used in the recent assessment is a traditional statistical approach using a generalized linear model (GLM; Nelder and Wedderburn 1972; McCullagh and Nelder 1989). As an extension of ordinary least squares linear regression, GLMs are capable of accommodating nonnormal error distributions by relating the expected ith value of the response variable to a set of predictor variables through a link function, where the link function is based on the assumed error distribution. Several CPUE time series were incorporated in the recent marlin assessments, each of which was standardized with some form of GLM (ICCAT 2006). For example, Diaz and Ortiz (2007) standardized catch rates from the U.S. pelagic longline fishery by accounting for factors such as year, area of fishing, gear characteristics, and fishing characteristics while also incorporating random interaction effects. The specification of random effects indicates that Diaz and Ortiz (2007) used a variant of GLM, referred to as a generalized linear mixed model (GLMM; Venables and Dichmont 2004). While incorporating fishing characteristics can account for some of the variability caused by a change in target species, the GLMMs did not directly address the overlap between fishing effort and marlin distributions.

Another approach under consideration is habitat based standardization (HBS). This is a deterministic method that estimates effective fishing effort by incorporating information on the vertical distribution of the species in relation to the distribution of fishing effort (Hinton and Nakano 1996). Information on vertical distributions are typically derived from analyses of archival tagging data (e.g., PSATs), and the distribution of fishing effort is estimated based on characteristics of the gear. The HBS approach has been applied and incorporated into assessments of large pelagics in the Pacific Ocean (Bigelow et al. 2002; Maunder et al. 2002; Hinton and Maunder 2004; Maunder et al. 2006; among others); however, in the Atlantic, HBS has been applied but not used in stock assessments because of criticisms over the ambiguity surrounding the relationship of these species to the amount of fishing effort imposed on them (Yokawa et al. 2001; Goodyear et al. 2003; Yokawa and Takuchi 2003).

The merits of both approaches to CPUE standardization warrant thorough evaluation. Since the aforementioned shift in target species resulted in a change in the depth stratum exploited by the pelagic longline fishery, it is likely that marlin catch rates were impacted by factors other than changes in abundance. The HBS and GLM approaches can account for this variability as long as catchability (q) is proportional to habitat type. However, it is difficult to effectively accommodate changes in exploited habitat if detailed information on habitat structure, marlin vulnerability as related to habitat, and the distribution of effort across habitats are unavailable. In the case of the 2006 marlin stock assessments, CPUE was standardized without directly considering changes in the habitats targeted by the fishery, resulting in steep declines early in the time series. These prominent features may be artifacts of a change in target species, yet they likely influence assessment results. The HBS approach can also be biased, however, because numerous factors can violate the assumption that q is proportional to habitat type. Some of these factors include inconsistent feeding behavior across vertical habitats, inconsistent fish behavior across time and space, inconsistent gear behavior with depth, and many others (Goodyear et al. 2003; Horodysky et al. 2004). Another drawback of HBS is that it is a deterministic approach and therefore does not allow a characterization of uncertainty. Since GLMs estimate parameters statistically, the error surrounding these estimates can be quantified.

In an effort to incorporate habitat information into CPUE standardization under a statistical framework, Maunder et al. (2006) described statHBS. This method estimates the habitat parameters of the original HBS method rather than deriving them from external data. This overcomes one of the main criticisms of HBS because depth and habitat utilization data do not determine vulnerability to fishing gear. Also, statHBS accommodates additional explanatory variables, as is possible with GLMs. The statistical nature of this model allows quantification of uncertainty and the application of model comparison and selection techniques. In fact, Maunder et al. (2006) compared various methods of CPUE standardization for bigeye tuna in the Pacific Ocean, and, through model selection, determined that the statHBS model fit best to the data. Also, Bigelow and Maunder (2007) used statHBS and model selection to determine which explanatory variables are most important in understanding catch rates of bigeye tuna and blue shark *Prionace glauca* in the Pacific. They concluded that habitat parameters (those related to temperature and dissolved oxygen) are more reliable for predicting catch rates than depth. Nevertheless, statHBS and other approaches are not immune to shortcomings imposed by inadequate observations, which can violate assumptions and produce inaccurate trends in relative abundance.

Clearly, the methods of CPUE standardization mentioned here have unique advantages and drawbacks. Since a lack of consensus over the approach used in the last stock assessment of Atlantic marlins existed among the SCRS, it is important to fully evaluate and compare the available methods. Furthermore, Ortiz (2006) emphasized the need for additional comparisons of CPUE standardization techniques for blue and white marlins, specifically. Comparisons of GLM and HBS methods have been performed on simulated (Goodyear 2003a) and actual catch data (Maunder et al. 2006), but the conclusions of these studies were contradictory; HBS methods were favored by Maunder et al. (2006) and the GLM approach was determined most reliable by Goodyear (2003a). Since CPUE time series are fundamental to marlin stock assessments, it is imperative that the approaches to standardization are fully evaluated. Choosing between GLM and HBS standardizations can substantially influence the outcomes of assessments and, therefore, may have significant management implications. For example, the application of HBS in an assessment of Pacific blue marlin resulted in a stable, if not increasing, index of relative abundance and a completely different conclusion regarding stock status as compared to an assessment tuned to a GLM standardization, which produced a downward trend (Uozumi 2003).

Habitat Utilization

Whether entered directly (HBS) or estimated (statHBS), habitat parameters can substantially influence indices of relative abundance. Thus, prior to assessing the utility of these methods of CPUE standardization, it is important to thoroughly evaluate scientific understandings of Atlantic marlin behavior and habitat utilization. Current knowledge regarding marlin habitats has, in large part, come from studies that used PSATs. Typically, these studies described habitat by reporting temperature and depth distributions for the tagged individuals. While this provides a valuable summary of habitat utilization, a thorough understanding of marlin distributions requires an explanation of the sources of variability within the populations. For instance, marlin habitats may vary ontogenetically, across regions and seasons, or in response to various environmental factors. In many ecological studies, the effects of these variables can be explained through statistical analyses, such as linear models. However, PSAT data present unique statistical challenges, causing a majority of studies to truncate the trends and report results as histograms representing mean behavior. This prevents the detection of significant sources of variation in the populations, which may substantially improve the accuracy of CPUE standardization methods that are habitat-based.

Determining an effective approach to the statistical analysis of PSAT data requires an understanding of the nature of the data. Since PSATs record numerous sequential measurements while attached to a fish, the measurements for one fish are likely more similar than those between fish, and measurements adjacent in time are likely more similar than those farther apart. As noted by Wilson et al. (2005), if the statistical method used for the analysis of PSAT data does not account for this autocorrelation, the power of a statistical test may be overinflated, potentially leading to erroneous conclusions that cannot be supported by the data. Typically, autocorrelated data resulting from multiple measurements within a single experimental unit are considered longitudinal data, and statistical methods capable of addressing their unique nature have been developed (Diggle et al. 2002). High frequencies of measurements obtained from PSATs, however, are considered intensive longitudinal data (ILD). The statistical methods developed for longitudinal data are designed for relatively few repeated measurements (roughly 10 or fewer) and may not be appropriate for ILD with multiple waves of measurements (Walls and Schafer 2006). Recently, statisticians in the social and health sciences developed statistical methods designed to analyze ILD (Walls and Schafer 2006) that may have great potential for the analysis of archival tagging data.

There are several models reviewed by Walls and Schafer (2006) that may translate to PSAT data analysis. Those that show the greatest promise are essentially variations of the original multilevel linear model (MLM) developed for analysis of longitudinal data (Laird and Ware 1982). Li et al. (2006) described a variant of the MLM that may apply to PSAT data. Through the incorporation of local polynomial regression, their functional data analysis (FDA) techniques allow the fixed and random coefficients of the MLM to vary nonparametrically over time. This may provide more flexibility in the statistical analysis by accommodating the variability among dives often observed in PSAT data.

Along with random variation between dives, large pelagic fishes often exhibit periodic trends in their dive behavior (Horodysky et al. 2007). Fok and Ramsay (2006) built upon FDA techniques by incorporating Fourier basis functions and B-splines to analyze ILD with periodic and nonperiodic trends. Their approach may be effective in addressing the cyclic trends observed in many PSAT data streams (e.g., dives in relation to diel cycles).

Another analytical approach that shows promise for PSAT data analysis is state-space modeling. This method has been in use for some time (Jazwinski 1970; Anderson and Moore 1979) and has recently been described for application to longitudinal data in a regression model framework (Dethlefsen and Lundbye-Christensen 2006; Ho et al. 2006). When presented in this manner, state-space models represent an extension of generalized linear models where the parameters are allowed to vary over time (Dethlefsen and Lundbye-Christensen 2006). This flexibility may help to describe the complicated habitat utilization profiles typically observed in PSAT data.

The models described represent potential approaches to robust statistical analyses of PSAT data. These analyses may identify significant, presently unconsidered sources of variation in the habitats utilized by the Atlantic marlins, and may address several uncertainties surrounding the relationships between marlin distributions and the distribution of commercial fishing effort. Since limited knowledge about fish (and gear) behavior has reduced confidence in CPUE standardization techniques that consider habitat (Goodyear et al. 2003; Horodysky et al. 2004), perhaps an improved understanding of habitat utilization would increase the value placed on these indices of abundance, potentially justifying their incorporation into stock assessments. It should be noted, however, that these methods still exclusively consider habitat and do not address the interaction between fish behavior and habitats. Thus, while understandings of marlin distributions may be improved, catchability is also a function of behavior, and this should be recognized when incorporating habitat into CPUE standardizations. Nonetheless, advancing knowledge regarding habitat utilization and potentially improving estimates of relative abundance may substantially improve the assessments.

Assessment Model

While the most recently applied stock assessment model (BSP) was useful for evaluating stocks in an entirely fishery-dependent context, there were potential sources of error that the model did not directly address. First, due to limited data, the BSP model relied solely on catch-and-effort data. This speaks to the importance of accuracy in estimating relative indices of abundance because changes in CPUE may considerably alter assessment results (Babcock 2007), especially when methods of standardization do not account for changes in target species (i.e., catchability). A sensitivity analysis using a range of indices of abundance may account for uncertainties associated with CPUE, but reliable indices facilitate accurate depictions of stock status. Furthermore, estimates of stock parameters in the recent assessments were constrained with prior distributions governed by the results of previous assessments. This biased the results and contributed to the uncertainty regarding stock status relative to MSY benchmarks (ICCAT 2006).

Also, the BSP model was relatively simple in that annual biomasses were aggregated across all ages in the population that were subject to exploitation. This assumed that, irrespective of age, these individuals were equally vulnerable to incidental capture by the fisheries. Since this may be unlikely, evaluations of population dynamics could improve from better understandings of the age composition of marlin catches. Some marlin growth data are available, but validated aging methods do not exist for adult marlins (Drew et al. 2006), and this information was deemed insufficient for incorporating age structure into the most recent marlin assessments. Also, necessary additional biological information regarding ages at maturity and sex ratios of the catch was lacking (ICCAT 2006). It has been suggested, however, that despite the lack of confidence in the aging data, certain age-structured models may improve marlin assessments (Restrepo et al. 2003) since relatively simple production models capture net effects of fishing and not detailed historical trends of growth dynamics, selectivity-at-age, and other population impacts (Hilborn and Walters 1992; Walters and Martell 2004).

There are several existing age-structured assessment models that do not rely directly on detailed catch-at-age data, and therefore their application to Atlantic marlin stocks may be worth consideration. One mode of imposing age structure is through relating estimated growth models, such as length (or weight) at age, to length frequencies of the catch. These integrated assessment models, such as MULTIFAN-CL (Fournier et al. 1998), Stock Synthesis (Methot 2000; NOAA Fisheries Toolbox 2009), CASAL (C++ algorithmic stock assessment laboratory; Bull et al. 2005), and others have proven useful when applied to large pelagic fishes. Porch (2003) used a state-space age-structured production model to assess the Atlantic white marlin stock; however, his approach was purely heuristic and not meant to influence management decisions, largely due to limited information for estimating selectivity at age. Another assessment approach that has been attempted for marlins involves a delay-difference model in which age structure is imposed on immature individuals only, based on an assumed selectivity at age (Cox et al. 2002b). This model was applied to several stocks of large pelagic fishes in the central North Pacific Ocean. While the approach was relatively simple, the estimates were similar to those of more complex assessments. Typically, ideal model complexity for a stock assessment is ultimately related to the data available (Walters and Martell 2004), yet, as exemplified by Cox et al. (2002b), additional complexity does not always result in a better understanding of stock status. In general, models that incorporate age/size structure are favored over less complex production models because they estimate trends in selectivity at age and can elucidate changes in growth patterns (Walters and Martell 2004). Thus, one or more of the proposed assessment models should at least be thoroughly evaluated and the results compared to those of the BSP model to see if increasing model complexity through the incorporation of age structure provides better information for managing Atlantic marlins.

Catch Data

In addition to addressing uncertainties pertaining to marlin habitats, CPUE standardization, and stock assessment models, there are numerous other sources of error that warrant attention. For instance, the historical catch database, which is the basis for marlin stock assessments, is incomplete (Restrepo et al. 2003). Since marlins are landed by commercial fisheries or directly by artisanal fisheries, they are difficult to monitor, causing many countries to inconsistently report landings or fail to report them altogether (WMBRT 2007). Gaps in the data are then filled in with estimated catches, which are based on the amount of target species landed. Also, landings typically do not include discards, a problem that may be exacerbated by regulations requiring live release. Individuals that were discarded dead were certainly subject to fishing mortality, and based on studies that estimated postrelease survival (Kerstetter et al. 2003; Kerstetter and Graves 2006b), a certain percentage of live releases also perish, depending on the species and gear used. Thus, any changes in release practices that are not documented further limit the ability to predict fishing-induced mortality rates. Atlantic marlins are subject to a range of illegal, unreported, and unregulated (IUU) fishing activities (for more on the complexities of IUU fishing, see Serdy 2011, this volume). While ICCAT has made recommendations to identify and combat IUU fishing (ICCAT 2004, Rec. 2003–16; ICCAT 2007b, Rec. 2006–12; ICCAT 2008, Rec. 2007–09), the practice continues, thereby compromising the accuracy of the catch database. Each of these factors potentially results in underestimated landings. Since the degree of uncertainty surrounding the inadequacies in the catch data are difficult, if not impossible to quantify, accounting for underestimated landings in the assessment is a significant challenge. At the very least, sensitivity analyses using reasonable ranges of unreported landings, and live and dead discards are encouraged. Management decisions, therefore, could be based on a range of stock status predictions for Atlantic marlins rather than fixed estimates.

Another problem plaguing marlin assessments is billfish misidentification. There is misclassification between the marlins (WMBRT 2007), but awareness of the uncertainty in billfish classification has increased in recent years (ICCAT 2006). This may be due, in part, to the recent verification of the existence of roundscale spearfish *Tetrapturus georgii* in the Atlantic (Collette et al. 2006; Shivji et al. 2006). At first glance, this species can easily be confused with white marlin and other spearfish. Since roundscale spearfish has only recently been verified, it is impossible to estimate historical proportions of marlin landings comprised of roundscale spearfish. Uninformed estimates of these proportions could be generated and sensitivity analyses performed, but estimating proportions with confidence requires extensive research on landings, distribution, and habitat utilization of roundscale spearfish. While current estimates suggest that roundscale spearfish make up roughly 27% of the "white marlin" catch in the western Atlantic, simulated changes in the proportions over time were shown to substantially impact assessment results (Beerkircher et al. 2009). Furthermore, a portion of reported billfish landings are determined in port on fish that have already been processed for sale. Since billfishes are more difficult to distinguish when dressed, this represents a substantial source of uncertainty in the catch database. Unfortunately, without regular tissue sampling for genetic identification, the issues regarding classification in billfish landings will likely persist for some time.

Life-History Characteristics

Finally, uncertainty regarding life-history characteristics can impact the accuracy of stock assessments and, as mentioned, has limited the choice of assessment models for Atlantic marlins. For example, sexually dimorphic growth (with females attaining larger sizes than males) is present in both species, especially blue marlin; therefore, it is likely that males and females differ in their susceptibility to fishing gear. Also, sexual dimorphism contributes to the difficulty of relating size and age in marlins, which further limits the ability to apply age-structured stock assessments. However, if unaccounted for, these growth dynamics could result in unforeseeable impacts to the populations. For instance, if the proportion of females (especially large females) removed from the population exceeds the proportional removal of males, then overall reproductive output could be compromised (Luckhurst et al. 2006). This decreasing fecundity may be undetected in stock assessments that do not consider sex-specific effects, potentially resulting in overestimates of MSY, but if the impacts are well understood, management could enact measures designed to protect the most productive components of the population. At a minimum, an understanding of the sex ratios of the populations as well as of the catch would be required to estimate population impacts such as these. While sex ratios of samples of the populations and of the landings have been estimated in some areas (de Sylva and Davis 1963; Baglin 1977; Arocha and Bárrios 2009), a thorough sampling of the landings has not occurred; thus, historical trends in sex ratios would be difficult to determine. Despite these challenges, estimating the sex-specific impacts of fishing on the populations using the available data may be worth consideration. This could be attempted in an assessment context with sensitivity analyses, or through simulations similar to those performed by Goodyear (2003b). However, it should be noted that comprehensive size- or age-structured assessments of the populations may require information concerning age-specific sex ratios, maturity, fecundity, natural mortality rates, understandings of the stock–recruitment relationships, and any related density-dependent effects.

The aforementioned analytical uncertainties regarding Atlantic marlin population analyses (i.e., model and estimation uncertainties related to CPUE standardization and the stock assessment process and observational uncertainties surrounding habitat data, catch data, and life-history characteristics) limit the ability to manage these stocks sustainably. It may be that imposing relatively strict management measures can account for uncertainties indirectly and marlin populations can be conserved in this way, but informed management decisions based on assessments that directly address uncertainties are more likely to be broadly supported. While this is a difficult task, some of the suggestions provided may prove effective. Overall, it is critical to the sustainability of Atlantic marlins that attempts are made to address and account for uncertainties surrounding their assessments.

Governance

The Atlantic-wide stocks of blue marlin and white marlin are susceptible to multinational commercial, recreational, and artisanal fisheries. As mentioned previously, assessments and management of these stocks fall under the jurisdiction of ICCAT's member nations, a collection of contracting parties that represent national interests. Regulations by ICCAT are either in the form of nonbinding resolutions or binding recommendations, and passage of these measures typically involves consensus among member nations. In 1995, ICCAT passed their first resolution pertaining to billfish, which encouraged live release from commercial and recreational fisheries. Since this initial resolution, several recommendations and resolutions have followed (Peel et al. 2003; WMBRT 2007).

Currently, Atlantic marlins are in phase 1 of a two-part stock rebuilding program (ICCAT 2007b, Rec. 2006–09). This phase will apply through 2010, with regulations affecting commercial and recreational fisheries. For pelagic longline and purse-seine vessels, landings of blue and white marlins are restricted to 50% and 33%, respectively, of 1996 or 1999 landings (whichever year was greater). Also, all marlins caught alive are to be released, though successful live release from purse seines may be challenging. For U.S. recreational fisheries, total landings are not to exceed 250 individuals per year for blue marlin and white marlin combined, and other nations with recreational fisheries are encouraged to develop minimum size regulations. The remaining management measures associated with phase 1 mainly pertain to reducing uncertainties in stock assessments by encouraging continued research on Atlantic marlins and maintaining and improving fisheries data collection practices, especially for artisanal fisheries.

In addition to international regulations, member nations may choose to impose further management measures on their respective fisheries. For example, the United States prohibits all commercial landings and trade of Atlantic marlins. This clearly emphasizes the value the United States places on its recreational fisheries; however, these fisheries are not immune to additional regulations. The annual allowable catch set by NMFS follows ICCAT's restriction at 250 blue and white marlins combined, and to attain this limit NMFS has established size limits for each species (2.51 and 1.68 m [99 and 66 in] lower jaw fork length for blue and white marlin, respectively). Furthermore, NMFS requires the use of circle hooks in natural baits for billfish tournaments and encourages the live release of all billfish caught recreationally, a practice favored by many billfish anglers.

Overall, the phase 1 regulations imposed by ICCAT will likely benefit Atlantic marlin populations to some degree. Increases in live-release practices are particularly promising, especially given that a substantial number of marlins are alive upon retrieval (haulback) of pelagic longline gear (Cramer 2000; Kerstetter and Graves 2006b). Also, when released from this gear, survival rates are likely to be high for both blue marlin (Kerstetter et al. 2003) and white marlin (Kerstetter and Graves 2006a). Furthermore, low postrelease mortality has been demonstrated in recreational fisheries for blue marlin (Graves et al. 2002) and white marlin, especially when circle hooks are used (Horodysky and Graves 2005; Graves and Horodysky 2008). Thus, when coupled with reduced landings, increased live-release practices should slow and possibly reverse downward population trajectories. If estimates of relative abundance are accurate, some evidence of population responses to these management strategies may already be observable (Figure 3), but stocks likely remain depleted and overfishing almost certainly continues.

The inability to eliminate or substantially reduce overfishing of Atlantic marlins has been considered a failure attributed to ICCAT (Peel et al. 2003). It should be noted, however, that due to overlapping distributions and differing biological characteristics, it is unlikely that ICCAT could ever achieve its goal of harvesting at MSY for all species under its purview. For instance, the fishing pressure associated with MSY for a target species may result in overfishing of nontarget species. Conversely, ensuring sustainable harvests of nontarget species may lead to considerable underutilization of target species. The prior scenario reflects the relationship between the Atlantic marlins, whose estimated fishing mortality rates exceed F_{MSY}, and various target species (bigeye tuna, yellowfin tuna, and swordfish), whose rates are close to F_{MSY}. However, the latter scenario represents a form of precautionary management where effort is controlled to achieve MSY for the species most vulnerable to overfishing. Given the short-term declines in profits that would result from such an approach, it is unlikely that ICCAT could reach consensus on measures that ensure sustainability of bycatch species at the expense of commercial revenue.

While it is improbable that ICCAT will reduce fishing effort to the extent necessary for rapid rebuilding of marlin populations, further management actions may prove beneficial. Since ICCAT relies on self enforcement by member nations, full compliance with additional measures may be unlikely; nevertheless, these measures, including encouraging live release and the use of circle hooks, may substantially reduce fishing mortality rates. However, if marlin populations do not respond to additional management actions, external influences may be required to achieve reductions in fishing pressure. There are several options related to protected species management that may be applicable to marlins, including the Convention on International Trade in Endangered Species of Wild Fauna and Flora, the protocol on Specially Protected Areas and Wildlife of the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region, and the U.S. Environmental Protection Agency (U.S. EPA; Peel et al. 2003). However, a petition to have white marlin listed as threatened or endangered under the U.S. ESA was not successful (see Importance section, this chapter). Beyond these management pathways, increased attention and interest by nongovernmental organizations, the public and the media could also be strong forces of influence over marlin bycatch. Thus far, these groups have expressed relatively little concern regarding the depleted biomasses and continued overfishing of marlins. If that changes, however, a successful campaign against products from fisheries that land marlins incidentally could encourage the industry to minimize marlin bycatch or risk declining demand. The evolution to "dolphin-safe" tuna has already exemplified the utility of consumer activism as an effective strategy for reducing bycatch in these fisheries (Hall 1998; Hall et al. 2000). Perhaps consumer-driven sustainability for other bycatch species could be attempted by demanding a more comprehensive label for these fisheries, such as certification via the Marine Stewardship Council or other programs. This could provide an incentive for ICCAT's member nations to abandon the status quo and enact holistic measures that promote ecosystem-wide sustainability.

In general, there has been relatively little action by ICCAT or external groups to ensure rebuilding of Atlantic marlins. Unfortunately, until management measures are designed to substantially improve the odds of rebuilding, the number of uncertainties surrounding marlin population assessments may actually facilitate inaction because it is difficult to confirm population responses with high certainty given the noise in the available stock indicators. Thus, marlin assessments may have produced overly optimistic or overly pessimistic portrayals of the stock conditions, rendering appropriate management actions difficult to discern unless uncertainties are addressed. However, even with improvements in data collection and statistical analysis, there will always be uncertainties surrounding assessment results. Such uncertainties should not be used to justify delayed management action.

Recommendations

Following years of overfishing, Atlantic marlin populations appear to be severely depleted. Unfortunately, there are compounding limitations to successful rebuilding and management of these populations. First, the historical catch data are incomplete and potentially flawed. In combination with relatively poor understandings of marlin biology, ecology and behavior, these limitations compromise the accuracy of stock assessments. Also, uncertainties regarding quantitative approaches exist in the assessments, which further limit the willingness of ICCAT's member nations to make management decisions that constrain the fisheries, and result in a lack of consensus within ICCAT regarding the status of the stocks. Since these uncertainties represent a roadblock to effective management, it is important that they are addressed to ensure that management measures are based on the best possible characterizations of the stocks. Moreover, member nations are responsible for the development of management measures and enforcing compliance among their respective fisheries. However, full compliance is difficult to achieve, so management actions should be designed to accommodate implementation error.

Clearly there are many difficulties concerning management of Atlantic marlins. Nevertheless, with substantial international support, addressing and accounting for many of these issues may be possible. Uncertainties surrounding the catch data must be considered; major sources of error include unreported landings and discards from commercial, IUU, recreational, and artisanal fisheries, as well as misidentification of billfishes. Expanding the coverage and responsibilities of fisheries observers should be employed to address these limitations and improve the catch data. In addition to comprehensive monitoring of catch, landings, and number and condition of released bycatch species, observers could obtain valuable scientific information, including sex ratios, removal of hard parts for aging purposes, tissue samples for genetic validation of species, and other potentially useful information (e.g., diet, maturity, etc.).

Beyond expanding observer coverage, there are further actions that should improve catch data. For instance, nations that fail to meet reporting obligations should be penalized, and in the cases where these nations lack a sufficient infrastructure to monitor their fisheries, appropriate assistance should be given to ensure that proper reporting can be achieved. For marlins in particular, documenting the status and biomass of discards is especially important because of recently imposed management measures requiring live release in longline fisheries. Previously, fish captured live may have been accounted for in total landings, but now that they are released, their encounter and fate must be documented or else CPUE time series and future assessments could be substantially biased. Also, since misidentification occurs not only at sea, but also in port, the establishment of a comprehensive port sampling program, where tissue samples are collected for genetic identification (verification) of species, would likely improve classification of billfish landings. Finally, concerted efforts to identify and quantify catches from IUU and artisanal fishing must be ongoing.

Additional uncertainties surrounding Atlantic marlins are related to the assessment process itself. Combined with improving the data, advancing quantitative approaches to population analyses will encourage international consensus over stock status determinations, thereby supporting the passage of sustainable management measures. With an initial focus on improving analyses of habitat utilization, evaluating methods for standardizing CPUE that appropriately consider habitat, and expanding the complexity of the current assessment approach, understandings of marlin populations should drastically improve. Without these advancements, a lack of consensus among

ICCAT's member nations over the stock status of Atlantic marlins is likely to persist, and necessary management measures may be resisted on the basis of uncertainty. It should be noted, however, that expanding the complexity of assessment models may substantially expand the data requirements; thus the suggested data collection improvements are a necessary first step.

Sustainability of Atlantic marlin populations is ultimately in the hands of the member nations of ICCAT. Many of the suggestions provided herein require management action, especially those related to improving the quality of the data. If enacted, these recommendations may improve the fisheries science and facilitate better understandings of Atlantic marlin populations, but their translation into sustainable management measures relies on the resolve of ICCAT's member nations. With many nations representing strong commercial interests, it seems unlikely that the contracting parties will manage for sustainability of bycatch species, such as Atlantic marlins, when commercial landings may suffer. Given this potential conflict of interest, it may behoove ICCAT to consider approaches such as time/area closures or alternative fishing strategies that minimize bycatch; otherwise, external pressure may be necessary to encourage precautionary management of all species under the purview of ICCAT.

Many of the world's fisheries that target HMS face bycatch problems similar to those described here. Therefore, a unified approach to monitoring, assessment, and management may increase the attention designated to bycatch and promote sustainability of these species. Globally, there are five regional fishery management organizations (RFMOs) that are responsible for international management of tuna and tuna-like resources, including billfishes. In addition to ICCAT, there is the Commission for the Conservation of Southern Bluefin Tuna, the Inter-American Tropical Tuna Commission (see Oh 2011, this volume), the Indian Ocean Tuna Commission, and the Western and Central Pacific Fisheries Commission. Currently, these RFMOs manage their respective fisheries independently; however, since each organization may be facing similar issues related to bycatch, coordinated efforts among the RFMOs may improve management efficiency and effectiveness. While previous collaborations have occurred (Majkowski 2007), we recommend that the five RFMOs collectively establish harmonized measures across the world's oceans that (1) improve reporting of landings, discards, and fishery practices and dynamics as related to nontarget species; (2) expand fisheries observer coverage and responsibilities to fully monitor international fisheries and to collect valuable scientific information; (3) develop a comprehensive international port sampling program for identification and sample collection; (4) monitor IUU and artisanal fisheries to the extent possible; (5) encourage and support ongoing advancements in quantitative approaches to evaluating stocks that characterize and reduce uncertainties and fully utilize available data; and (6) with a focus on the results of stock assessments, follow a precautionary approach to fisheries management that considers the whole ecosystem and ensures the sustainability of target and nontarget species (for more on ecosystem approaches to fisheries management, see Box 1). Cohesive adoption of these recommendations by the tuna RFMOs would promote consistency and cooperation across international fisheries. This would encourage the sustainability of fisheries worldwide and would especially benefit bycatch species susceptible to overexploitation, such as the Atlantic marlins.

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Box 1: A Brief Overview of Ecosystem Approaches to Fisheries Management

The effects of fisheries often extend beyond those directly related to target species and include impacts on various components of the ecosystem, such as non-target species, habitats, and trophic structure. Thus, to achieve sustainability of fisheries, managers must consider all potential fishery impacts and impose regulations that facilitate long-term ecosystem stability. Historically, most fisheries have been managed from the perspective of maximizing the sustainable yield of a target species (i.e., a single-species approach); however, recognition of the importance of a holistic approach has prompted a paradigm shift in fisheries management toward encouraging ecosystem-wide considerations. While ecosystem approaches to fisheries management (EAFM) have been described extensively using various terms and associated definitions (see Browman and Stergiou 2005; Christie et al. 2007; Marasco et al. 2007; Murawski 2007; and Bianchi and Skjoldal 2008 for reviews), the basic principles recognized by most governing bodies are consistent (Murawski 2007). As an example, the United Nations formally accepts the following definition (FAO 2003):

> [A]n ecosystem approach to fisheries (EAF) strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic, and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries.

While the broad acceptance of EAFM among national and international policy agencies represents a significant shift in philosophy and is potentially crucial to long-term fisheries sustainability, universal implementation is unlikely in the near future (Christie et al. 2007; Marasco et al. 2007). The increased complexity and dimensionality associated with ecosystem approaches introduce a suite of challenges at the scientific level (e.g., understanding the temporal and spatial variability in climate, habitats, biodiversity, food web dynamics, population structure and genetics, and physical and chemical properties of the ecosystem, as related to anthropogenic impacts, particularly fishing), which magnify challenges common to fishery management, such as establishing institutional hierarchy, balancing socioeconomic concerns with scientific advice, determining effective conservation and management measures, encouraging stakeholder participation, incorporating uncertainty, and enforcement (see Browman and Stergiou 2005; Marasco et al. 2007; Bianchi and Skjoldal 2008; Ruckelshaus et al. 2008) for EAFM implementation guidelines, considerations, and challenges).

Despite substantial obstacles, various forms of EAFM have been implemented throughout the world (Murawski 2007). For example, Alaskan groundfish fisheries have been managed under an ecosystem approach for several years, and none of the target species are currently considered overfished (Witherell et al. 2000; Ruckelshaus et al. 2008).

(Box continues)

Box 1. Continued.

Generally, comprehensive EAFM require substantial institutional, financial, and technical support, which are typically more available in developed nations. However, EAFM can be implemented in varying degrees and can also be adopted by countries with limited resources, as exemplified in the management of nearshore Philippine marine fisheries (Christie et al. 2007; Pomeroy et al. 2010).

Ecosystem approaches are becoming more prevalent among management agencies around the world, but due to the scale and complexity of these methods, they are yet to be the driving force behind most management decisions. Over time, fisheries management will likely rely more heavily on EAFM as they may be fundamental to the sustainability of global fisheries; however, the overall evolution to universal EAFM is likely to be slow and incremental (Murawski 2007).

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