ARTICLE

Understanding Maximum Size in the Catch: Atlantic Blue Marlin as an Example

C. Phillip Goodyear*

1214 North Lakeshore Drive, Niceville, Florida 32578, USA

Abstract
    Mean and maximum sizes in the catch are readily understood by both fishermen and scientists as important indicators of population health, but the maximum is more complicated to interpret because it increases with the number of observations. Size distributions of catches were computed for stable age distributions of hypothetical Atlantic populations of Blue Marlin *Makaira nigricans*. Fishing mortality rates were selected that reduced the population per age-1 recruit by 25, 50, 67, 75, and 90% by number from the unfished state. A new metric, NZ50, was applied to evaluate the performance of maximum size as an indicator of population status. Sample sizes required to include large marlin in a set of observations increased to disproportionately large numbers with increased fishing. With the best estimates of growth and a natural mortality of 0.1, the number of random observations required for a 50% probability of including a 350-cm individual increased by about 43% when the population was depressed by 25%. This value rose to more than 50-fold when the population was reduced below 10%. In contrast, mean lengths were reduced by only 1.6% to 14% and mean weights by 5% to 45% for the same range of fishing. These results provide quantitative evidence confirming the view that a diminished number of large fish is a sensitive indicator of excessive fishing, even when mean size of the catch shows only a small change. Increased catches above large size thresholds or nearing historical maxima could be sensitive indicators of stock recovery. Measures of the frequency of occurrence of individuals above some threshold defined for large fish will generally be superior to the maximuma observed in a sample (or set of samples) as a biological reference criterion because of the stochastic nature of individual observations.

    Mean and maximum observed sizes tend to decline with increasing fishing mortality, a trait easily recognized by fishermen and scientists alike. Consequently, such data are informative indicators of population health and receive particular scrutiny during the fisheries management process. Both measures reflect the lower survivorship to larger, older sizes in the population that accompany fishing and can be estimated for random samples of a population or catch. The lack of a notable declining trend in Atlantic population of Blue Marlin *Makaira nigricans* average sizes has been used to argue that assessment results showing a major decline in the stock are in error (Suzuki 2001). However, in previous work I showed that in fast-growing, long-lived species like Blue Marlin, mean length may decline only slightly even with a considerable fishing-induced population decline (Goodyear 2003). In this earlier study, the population declined because of reduced recruitment and because the number of survivors to old age was reduced by fishing. The latter effect is responsible for the expected reduction in mean size, but the very fast initial growth of Blue Marlin minimizes the effect because the large number of young, but nevertheless large, individuals in the population mitigates the effect of the removals of the older fish on population mean size. This characteristic is, in part, responsible for the lack of a clear trend in Blue Marlin mean sizes over time in the Atlantic Blue Marlin data that persists in the most recent assessment analyses in spite of the population decline documented therein (Anonymous 2011, 2012). At the same time, anecdotal evidence suggests that large Blue Marlin were more

common in the past. As of this writing for example, the International Game Fish Association recreational all tackle record for the Atlantic was 636 kg in 1992 and 624 kg in 1982 for the Pacific (www.igfa.org October 2014). These records are two to three decades old despite remarkable increases in technology and effort and seem inconsistent with the apparently constant average size in the assessment data.

Mean size is not dependent upon the number of observations but, rather, becomes more precise as the number of observations increases. In contrast, the observed maximum tends to increase with the number of observations in the sample. This tendency results from the increased likelihood of including an observation from the upper tail of the distribution of sizes in the population from which the larger sample is drawn. When fishing is distributed across a broad range of ages, the decline in maximum observed size is the result of reduced survival to the older ages, which typically include the largest individuals in the population. Although the mean is easily estimated and understood, the utility of observations at or near the maximum is less obvious. This study investigates via a new metric, NZ50, the behavior of maximum observed sizes in the catch from a hypothetical Blue Marlin population as a function of sample size and fishing and natural mortality. The results show that fishing causes remarkable increases in the sample sizes required to observe individuals near the upper limits of the unfished population maxima.

METHODS

The likely maximum observed value in a sample of observations depends on the joint probability for the number of observations and the cumulative frequency distribution (CDF) of sizes within the population. Consequently, both variables must be involved in a metric to quantify maximum size. To characterize the effect of the number of observations, I constructed a new metric, NZ50. This metric is the least number of observations required of a random sample to include one or more individuals equal to or greater than a specified size in 50% of such samples (i.e., the smallest number of observations to include fish at least that big half the time). The NZ50s for Blue Marlin were estimated by conjoining the values of the cumulative probabilities (p) for a specific (threshold) sizes with the corresponding values of the cumulative probabilities (λ) of medians of sample maximum probabilities by sample size (Figure 1).

Statistical model.—Monty Carlo methods were employed to estimate the cumulative distribution of sample maximum probability values as a function of the numbers of observations. This was done by drawing 10^6 sets of samples of 1–100,000 random observations each from a standard uniform distribution. The random numbers were drawn using the FORTRAN intrinsic function RANDOM_NUMBER(), which provides uniformly distributed pseudorandom numbers within the range $0 < 1$ with a period of approximately 10^{18}, thus minimizing any effects of intrinsic patterns in the random number sequences. The uniform distribution was employed so that every possible value had an equal probability of being "sampled" in a random set of observations. This provided a cumulative frequency distribution of maximum probability levels observed for each number of observations in a sample. The cumulative distribution of the medians from each of these sample maximum probability value distributions by sample size provided the CDF (λ) for NZ50.

Population model.—I combine the NZ50 statistic with data on the sizes of catches drawn from the computed stable age distributions for various vectors of fishing and natural mortality. Most of the size data collected for the Atlantic Blue Marlin fisheries are recorded in units of lower-jaw fork length (LJFL;
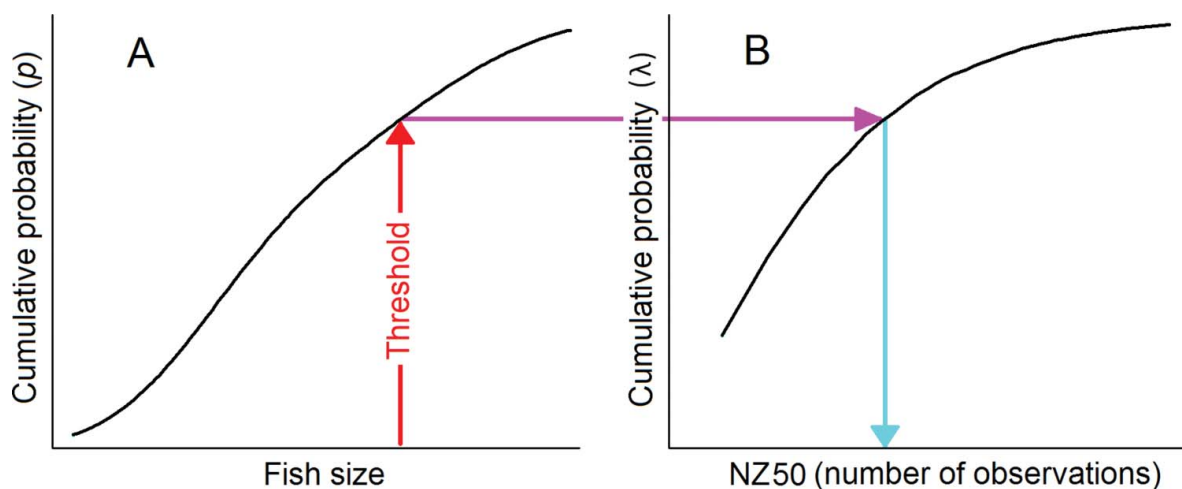

FIGURE 1.   Illustration of the method used to estimate NZ50 for a specific threshold fish size. **(A)** The probability (p) for that threshold size is first estimated from the cumulative probability of fish sizes. **(B)** This probability level is used to index the probability, λ, from the cumulative distribution of NZ50 to then determine the value of NZ50 for that specified size.

Anonymous 2011), and this metric is used herein. Where appropriate conversions are needed for comparisons, lengths were converted to weights using the weight on length regressions of Prager et al. (1995). The model adopted explicitly includes variation in size at age and sex (S) at 101 explicit annual ages (ages 0–100) to minimize possible effects of truncating the age structure. No plus group was assumed. This presumes that survivorship beyond age 100 becomes a vanishingly small proportion of the population. Age was further partitioned into 52 weekly intervals per year so that there were 5,252 discrete time intervals (T) in the analysis. Fishing and natural mortality did not vary by sex or age within each analysis.

Each sex is modeled separately to incorporate sexually dimorphic growth. The size distribution is characterized by partitioning each sex into 2,001 phenotypic morphs (O) representing portions of the population that differ in length at age. The number of increments was simply an arbitrarily large value. The length of each morph of each sex at each week (L_{SOT}) was determined from the sex-specific population mean length at age, sex, and week by dividing the range $\pm$ 5 SD from the mean into 2,001 equal increments. This approach to characterizing growth is an "assignment-at-birth" (Kirkpatrick 1984), in which the growth of each individual follows a distinct pattern that is completely determined at some initial (prerecruit) stage. Population characteristics are then evaluated by summing over the morphs and sexes. This set of assumptions partitions the population into just over 21 million sex-morph-week bins. Matrices of the numbers of survivors (N_{SOT}), catches (C_{SOT}) and their lengths (L_{SOT}) were retained for analysis for each condition evaluated during the study.

Recruitment occurred at the beginning of the first week ($T = 1$). Under the assumption of an equal proportion of males and females, the initial abundance of each morph was 0.5 times the cumulative probability (θ) within the length interval represented by the growth morph (O), as estimated with the Fortran intrinsic function DNORDF(). For each sex and morph (O), the initial recruitment, $N_{\mathrm{SO1}}, = 0.5(\theta_O)$ .Total recruitment sums to 1. The number of survivors (N_{SOT}) to the beginning of succeeding weeks, is

$$N_{\mathrm{SOT}} = N_{\mathrm{SO1}}\exp(-\mu_T),$$

where μ_T is the cumulative total mortality suffered by morph O of sex S from recruitment to the beginning of weekly time interval T, which is

$$\mu_T = \sum_{t=1}^{T-1} (M_t + F_{Ot}).$$

The seasonal natural (M_t) and fishing (F_{Ot}) mortalities used in the present evaluation were 1/52 of the annual assumed rates and were not varied by age or sex within each analysis, except

that fishing mortality for growth morphs was set to zero when their sizes were below 100 cm LJFL. Catch in numbers for each sex-age morph each period (C_{SOT}) is

$$C_{\mathrm{SOT}} = \frac{N_{\mathrm{SOT}}F_T[1 - \exp(-(F_T + M_T))]}{(F_T + M_T)}.$$

Because N_{SOT}, C_{SOT}, and the mean length (l_{SOT}) of each age-sex morph are known for each season of each year, size frequencies of the population and catch can be easily constructed. The mean length of the catch (τ), for example, is given by

$$\tau = \frac{\displaystyle\sum_{S=1}^{2}\sum_{O=1}^{2001}\sum_{T=1}^{5252} C_{\mathrm{SOT}}l_{\mathrm{SOT}}}{\displaystyle\sum_{S=1}^{2}\sum_{O=1}^{2001}\sum_{T=1}^{5252} C_{\mathrm{SOT}}}.$$

Growth.—Blue Marlin clearly exhibit sexually dimorphic growth (Wilson 1984; Cyr 1987; Boggs 1989; Wilson et al. 1991; Su et al. 2013), but mean sizes at age and asymptotic maximum sizes (L_∞) by sex are not known with precision. The largest female reported in Hill et al. (1989) for Pacific Blue Marlin was estimated to be 22 years of age based upon both dorsal spine and sagitta counts. The largest male sampled in that study (170.3 kg) was estimated to be 14 years of age and the oldest male (estimated age 18) was just above the mean size. Wilson's (1984) study provided similar age and size estimates. Prince et al. (1991) were able to use daily otolith rings to characterize Blue Marlin growth through the first 16 months with reasonable certainty for a few individuals. Their data demonstrated that many Blue Marlin reach 190 cm LJFL before they reach 16 months of age. Mean lengths at age for the first 16 months of life from Prince et al. (1991) are concatenated (with smoothing) with sizes for older fish from the von-Bertalanffy models by sex from Wilson (1984), which corresponds to the methods used in Goodyear (2003). Variation in size at age of each sex was normally distributed about mean lengths from this growth model with a SD of 0.12 for each sex (e.g., Prager and Goodyear 2001; Goodyear 2003). Growth was assumed independent of population density. The assumptions I used for growth and model treatment of variation in size with age (i.e., lengths by sex and age and example distributions of size frequencies for each sex at the beginning of age 20) are presented in Figure 2.

Natural mortality.—Natural mortality (M) is notoriously difficult to estimate and especially to separate from total mortality (Z) in fished stocks. In its most recent assessment of the Atlantic Blue Marlin fishery, the ICCAT Billfish Working Group evaluated a range of M from 0.07 to 0.19 about a central estimate of $M = 0.139$ (Anonymous 2012). This value was loosely based on a longevity estimate of 27 years for a single individual in a study of Pacific Blue Marlin (Hill et al. 1989),
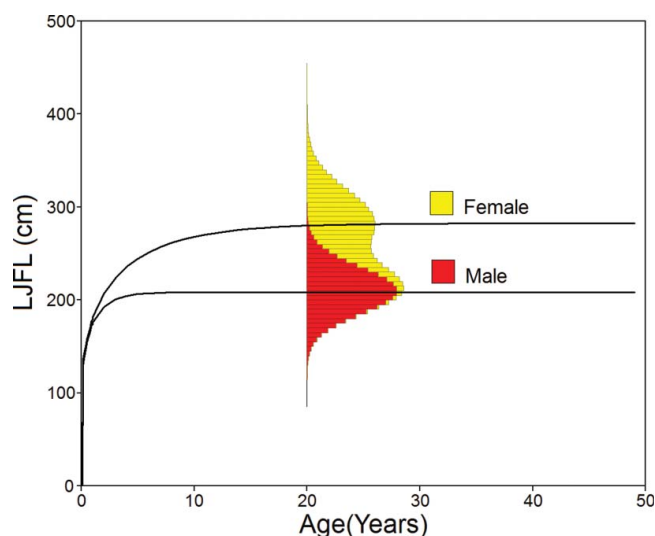
FIGURE 2. Mean lower jaw fork length (LJFL) at age of male and female Atlantic Blue Marlin assumed in this analysis. The histogram illustrates the sex composition of the distribution of sizes about the mean at the beginning of the year at age 20.

which imparted great power to that single oldest age determination. These considerations and a number of other features led Prager and Goodyear (2001) using the same methods and data to select $M = 0.10$ for fully recruited ages, as I did again here for a best estimate for the purpose of this study. Nonetheless, the true value of M is clearly uncertain, and I include a range of natural mortalities in five increments of 0.05 from $M = 0.05$ to 0.25 to explore the consequence of this variable on the mean and maximum sizes in the catch.

Fishing mortality—Fishing reduces mean size in the catch by reducing survivorship to old age. Based on the paucity of Blue Marlin below 100 cm LJFL in landings and observer data (Goodyear and Arocha 2001; Anonymous 2011) fish do not appear in the fishery until they reach about 100 cm LJFL. To accommodate this feature, fishing mortality was set to zero for growth morphs that were smaller than 100 cm LJFL at the beginning of a week. Otherwise fishing mortality applied equally to all ages and sexes in the population. The analyses here include fishing mortalities that result in declines in the population number per age-1 recruit to 0, 25, 50, 67, 75, and 90% of the unfished condition for each level of assumed natural mortality. For the unfished condition, the age frequency distribution for the population (N_{SOT}), where $L_{SOT} \geq 100$ cm LJFL, was substituted for the age frequency of the catch.

RESULTS

As the number in a sample declines to a single observation, λ from the CDF of NZ50 approaches 0.5 (Figure 3). This characteristic simply reflects the fact that on half the occasions in which there is only one fish in a sample, it will be equal or larger than the population median. Accordingly, the size at
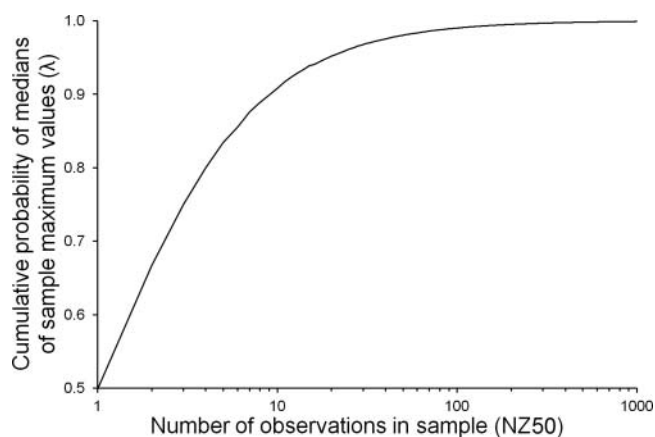

FIGURE 3. Cumulative probability of NZ50 (λ). The values of λ were estimated as the medians of the maximum observed probabilities in 10^6 sets of samples of 1–100,000 observations each from a standard uniform distribution (only sample sizes of 1 to 1×10^3 are included in the figure).

NZ50 is the median size in the population when the samples consist of a single observation each. Because samples must consist of integer values, the λ distribution is inherently discrete but it approaches a continuous distribution with increasing sample size. The median value for the maximum observed probability in samples increases with increasing sample sizes (Figure 3). I exploit this property to quantify the effects of fishing on maximum observed size.

Numbers at length in the sex-morph-week catches were accumulated into cm-length bins to provide the cumulative frequency distributions of the catch (the CDFs) from the stable age distribution for each level of assumed fishing and natural mortality (e.g., Figure 4 for $M = 0.10$). Values of NZ50 at 275, 300, and 350 cm LJFL were estimated from the cumulative probabilities of lengths (p) for each fishing–natural
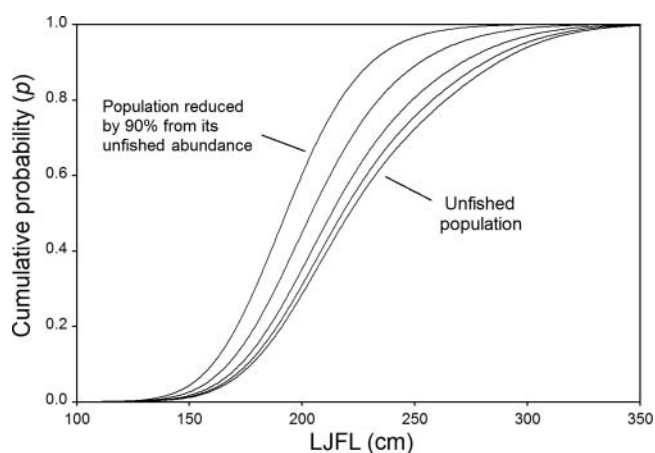

FIGURE 4. Cumulative probability distributions (p) for the lower jaw fork lengths (LJFLs) of Atlantic Blue Marlin catches, assuming a mortality rate of $M = 0.10$, and populations reduced to 0, 25, 50, 67, 75, and 90% of the unfished condition (per recruit). The curve for the 25% reduction is omitted for clarity.

mortality combination at each threshold length, using the distribution of λ. Note that a sample in this context could represent a set of observer-sampled measurements of the catch during a single fishing trip, or all of the individuals caught during some arbitrary time interval (day, month, year, etc.). The impact of fishing was assessed by the proportional change in mean lengths of the catch (Table 1) and in the NZ50 at 275, 300 and 350 cm LJFL (Table 2; Figures 5, 6).

As anticipated, mean lengths of the catch declined as total mortality increased (Table 1). With no fishing, the mean lengths declined from at $M = 0.05$ at 235 cm LJFL to $M = 0.25$ at 215 cm. The addition of fishing mortality further reduced the mean lengths of the catch with maximum reductions of about 13–14% at the most intensive levels of fishing considered. Because weights are a cubic function of length, the corresponding reductions in mean weights were greater, 41% to 43% respectively. These results are consistent with my previous findings for Atlantic Blue Marlin (Goodyear 2003).

The number of samples required to maintain the same probability of observing a large Blue Marlin was much more responsive to fishing-induced declines in the age structure than was the mean size. The NZ50 increases with increasing natural mortality and with increasing reference lengths (Figure 5). For example, for the scenario where the simulated population was depleted to 75% of its unfished state and assuming $M = 0.05$, a random sample of the catch consisting of only four observations would include a marlin of at least 275 cm LJFL half the time (Figure 5). The equivalent number (NZ50) increases to about 27 when the population is reduced by 90% from its unfished state. The comparable values for NZ50 at $M = 0.1$ increased from 5 to about 105 observations for the highest level of fishing examined. The average 350-cm Blue Marlin weighs about 470 kg (slightly more than 1,000 lb), a notable reference size among recreational fishermen (a so-called "grander"). At $M = 0.1$, the inclusion of a 350-cm LJFL marlin in half of samples would require about 224 individuals per sample before fishing (Table 2). The NZ50 increases

sharply with fishing, rising to more than 10^5 observations needed if the population per recruit is reduced to 10% of the unfished state. The corresponding percentage increase in required sample sizes ranges from about 5,000 for $M = 0.05$ to the tens of thousands or more at higher levels of M (Table 2).

The impact of fishing on the availability of large marlin to fishermen can be expressed as the proportional increase in NZ50 from its value for the unfished state. This proportion increased with fishing and reference size at each level of natural mortality examined (Figure 6). For each level of M considered, the increase was more than 50-fold at a reference size of 350 cm LJFL if fishing reduced the population by 90%. At the best estimate of $M = 0.10$, the ratios of fished : unfished NZ50 were about 2.7, 6.5, and 14 for fishing levels producing 50, 67 and 75% declines, respectively, in the population per recruit. This means that at a fishing rate that reduces the population per recruit to 25% of its unfished level, a fisherman, on average, would need to catch more than 14 times more Blue Marlin to have a 50% probability of including a "grander" among his catch. Higher fishing intensities increase this statistic rapidly such that at a per-recruit stock size of 10% of the unfished state, an individual fisherman would have to catch about 500 times more marlin to encounter an individual of that size.

DISCUSSION

The availability of the very largest fish in a population is often of special interest to recreational fishermen, and these fish can fetch a premium price for commercial interests. A common theme in finfish fisheries is that the abundance of large fish declines when a fishery develops. This pattern is as true for major commercial fisheries in oceans as it is for Bluegill *Lepomis macrochirus* (e.g., Coble 1988), or Largemouth Bass *Micropterus salmoides* (e.g., Seidensticker 1996) in lakes and ponds. Part of this decline is often the consequence of a general population reduction brought about by the fishing removals. The availability of large individuals to fishermen

TABLE 1. Mean lower jaw fork length (LJFL) of the catch and percentage reduction in mean LJFL (Pct. red.) from the unfished condition for various assumed levels of natural mortality (M) and at the specified levels of fishing-induced reductions in stock size per recruit. The mortality rate $M = 0.10$ (gray shading) was selected as the best estimate among the alternatives evaluated.

Stock decline (%)	Natural mortality (M)									
	0.05		0.10		0.15		0.20		0.25	
	Mean LJFL	Pct. red.	Mean LJFL	Pct. red.	Mean LJFL	Pct. red.	Mean LJFL	Pct. red.	Mean LJFL	Pct. red.
0	235	0.0	228	0.0	222	0.0	218	0.0	215	0.0
25	232	1.1	224	1.6	218	1.8	214	2.0	211	2.0
50	228	3.0	218	4.1	212	4.6	208	4.8	205	4.9
67	222	5.2	212	6.8	206	7.3	202	7.5	199	7.5
75	218	7.0	208	8.7	202	9.2	198	9.3	195	9.3
90	204	12.9	195	14.3	191	14.3	188	14.0	186	13.5

TABLE 2.   Sample sizes required to have an equal probability of observing a 350-cm (lower jaw fork length) Blue Marlin (NZ50) and the percentage increase relative to unfished levels (Pct. incr.). The mortality rate $M = 0.10$ (gray shading) was selected as the best estimate among the alternatives evaluated.

Stock decline (%)	Natural mortality (M)									
	0.05		0.10		0.15		0.20		0.25	
	NZ50	Pct. incr.	NZ50	Pct. incr.	NZ50	Pct. incr.	NZ50	Pct. incr.	NZ50	Pct. incr.
0	126	0	224	0	379	0	611	0	959	0
25	154	22	320	43	611	61	1,105	81	1,901	98
50	225	79	611	173	1,457	284	3,152	416	6,307	558
67	383	204	1,457	551	4,469	1,079	11,811	1,833	28,233	2,845
75	620	392	3,152	1,307	11,788	3,009	36,993	5,953	$>1 \times 10^5$	1×10^{4a}
90	6,438	5,010	1×10^{5a}	5×10^{5a}	$>5 \times 10^5$		$>5 \times 10^5$		$>5 \times 10^5$	

[a]Approximation.

lessens in part because of population declines in response to the harvest removals. More often, but sometimes less appreciated, is the progressive reduction in numbers at the oldest ages where the larger sizes predominate because of their accumulated exposure to risk of capture (a "catch-curve" effect). The latter effect manifests as a downward shift in the mean size of the catch or population. If the population is not overfished, neither its overall reduced abundance relative to the unfished state nor the change in mean size reflect how profoundly the abundance of large fish can actually change with fishing.

With a natural mortality of $M = 0.1$ the number of survivors after 25 years diminishes to about 8% of its previous level in the absence of fishing. The addition of fishing at $F = 0.1$ for a like period further reduces the number of survivors to about 0.7% of its original level. Continuing this scenario, the number of survivors after 50 years is less than 1%, and by 100 years it is diminished by more than 2 orders of magnitude from its otherwise similar, but unfished, value. As evidenced by the effect on mean size of the catch, fishing influences the size composition of the population. As fishing increases, the
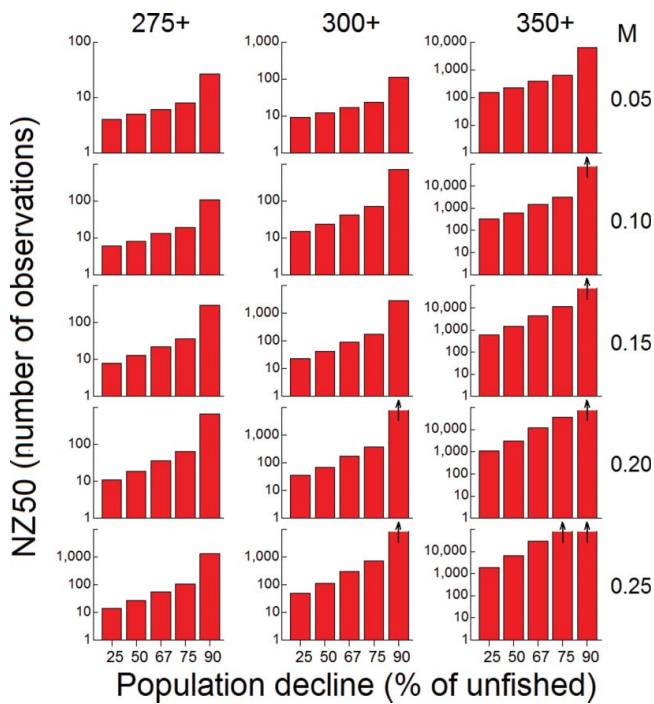

FIGURE 5.   Numbers of observations required to have a 50% chance (NZ50) of observing a Blue Marlin equal to or greater than specified size thresholds (275+, 300+, and 350+ cm [lower jaw fork length]) for various assumptions about natural mortality (M) and fishing.
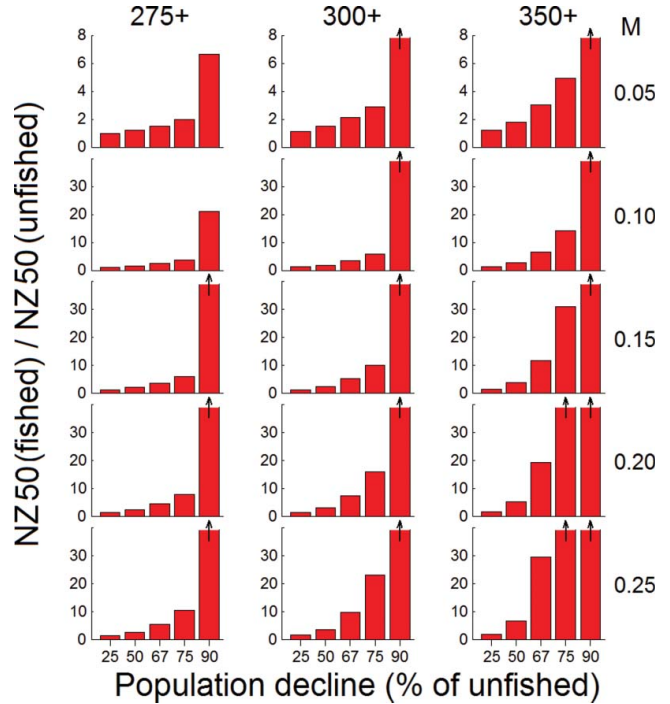
FIGURE 6.   Ratios of fished/unfished NZ50 for Blue Marlin equal to or greater than specified size thresholds (275+, 300+, and 350+ cm [lower jaw fork length]) and alternative assumptions about natural mortality (M) and fishing.

largest individuals in the population become progressively predominated by the relatively greater numbers of the fastest-growing individuals within younger age-groups. These fish have not suffered as much from the cumulative effects of fishing as have their older counterparts and progressively predominate the upper tails of the distributions of sizes as mortality increases. In the case of Blue Marlin these individuals are also all females. Their presence also buffers mean size against the reductions that otherwise would accompany the radical declines in abundance among the oldest ages in the population. It is worth noting that this shift in the age composition of the fastest growing fish happens without any change in the growth of individuals within the population. This phenomenon also changes sampling probabilities for obtaining specimens for growth studies that may cause unanticipated biases in growth-study results (e.g., see Goodyear 1995). In particular, there may be a tendency to actively seek out the largest individuals encountered in catch samples so that they may be included in growth studies. This effect will promote upward bias in estimated growth rates. It can be important, and it will be more influential as fishing reduces the population size. If examined through time, this phenomenon can promote a false impression of density-dependent growth.

The proportion of the fast-growing young individuals in the larger size-classes diminishes with increasing size. Other things being equal, the very largest fish in a population would be expected to be the fastest growing individuals of the oldest surviving year-class in that population. The size effect of long-term exposure to mortality is greatest in the upper tail of the size distribution, i.e., on the oldest of the biggest fish. This is why fishermen can perceive the disappearance of the really big fish even while the sizes of the most of their catch changes little. Because mortality is a stochastic process (fractions of fish do not exist, they either die or do not) some of the very largest individuals may sporadically persist even in a heavily fished population and be encountered by a fisherman. Consequently, there is always a chance to catch a fish of record or near-record size, albeit at a much reduced probability. The NZ50 expresses that likelihood as the number of fish that would need to be caught by the average fisherman to have a 50% chance to include one greater than or equal in size to some threshold value. Fishermen often vary in skill gear-type use; they may fish in different areas; and the distributions of their targets can vary by size, sex, time, and other factors. Because of these factors NZ50 will differ with fishermen skills, their use of dissimilar gears, and the geographical area selected for fishing (i.e., where the relative abundance of marlin varies by size). These differences reflect individual catchabilities that are partitioned differently among fishermen from the aggregated average (assumed here to be constant by age, sex and size). However, the values of the fished/unfished NZ50 ratios for individual fishermen are unaffected by variability in catchability ($q > 0$), when evaluated for the same size threshold and CDF.

Because the data available to judge changes in Atlantic Blue Marlin catches are not generally partitioned by sex, the model used here combines both males and females when accumulating the size composition of the catch. Males influence mean catch lengths for each natural and fishing mortality combination examined, but because of the large difference between male and female growth, only females contribute in any meaningful way to NZ50 estimates for thresholds above about 300 cm LJFL. For similar reasons, values of NZ50 and particularly, NZ50 ratios for larger threshold sizes would be relatively unaffected if lower adult natural mortality exists for female versus male Blue Marlin, as suggested by Su et al. (2013).

Changes in NZ50 and in estimated population abundance relative to the unfished state are different but interrelated measures of stock status. The NZ50 represent the numbers of fish needed to be caught (or sampled, etc.) to observe a threshold size, not the effort needed to catch them (i.e., they reflect the CDF of size in the population, and not its abundance). The effort needed to obtain the required catch obviously varies with the absolute number available. If recruitment were to be unaffected by the size of the spawning stock, then population abundance would decline and NZ50 would increase for any large size threshold when a population is fished. The same is true if recruitment declines with declines in the spawning stock, but the population numbers will decline more than predicted by the per-recruit analysis reported here. At least in terms of population models, this is the most common circumstance (e.g., Beverton–Holt stock–recruitment functions; traditional logistic surplus production models). Even for species where recruitment increases when the population declines due to fishing (e.g., the Ricker stock–recruitment function) the excess recruitment is removed by fishing at equilibrium, such that the absolute number of survivors to the oldest and largest ages in the population must also decline with fishing. Consequently for Blue Marlin, and as a more general rule when catch is distributed across multiple age-classes, fishing will increase both NZ50 and the amount of effort required to catch them. A special case may exist where the maximum per capita reproductive value of an individual occurs at some intermediate size of individuals within a population, as for example, among species such as groupers which change from female to male as they age.

In my study, higher M led to greater values of NZ50 for each size threshold and, more importantly, for each level of fishing. For example, in the 75% stock decline experiments, at $M = 0.1$ the fished/unfished NZ50 ratio increased about 14-fold from a little over 1 in 220 to about 1 in 3,200 (Table 2). In contrast, at $M = 0.20$, the fished/unfished NZ50 ratio increased about 60-fold from a little over 1 in 600 to 1 in about 37,000 (Table 2). At higher natural mortality rates the relative impact of fishing on the availability of large fish to fishermen becomes even more intense such that they could not be reasonably estimated for the higher fishing rates (Table 2). It is also

noteworthy that many of the sample size increases contemplated in these ratios would probably be impossible without increasing catch, if even then so.

Information on Blue Marlin growth could be significantly improved with additional study. Prince et al. (1991) note that Blue Marlin are among the fastest growing teleosts during their first months of life. By 16 months of age they attain an average of 91% for males and 67% for females of the asymptotic mean lengths assumed in this study and about 80% of the mean length of the 1971–2000 ICCAT catches (Goodyear 2003). Taken together, this information indicates that after a very fast initial phase, Blue Marlin growth declines rapidly but probably continues indeterminately towards some asymptotic maximum average size. I chose to adopt Wilson's (1984) von Bertalanffy representation of postjuvenile growth for convenience. The paucity of size-at-age data in the published literature, and particularly for the older fish, seriously undermines the fitted estimates of L_∞ in the few available studies. On the other hand the predicted size compositions of the catches from these growth models are generally consistent with the sizes actually encountered in the fisheries, so improvements in growth models may be more important for the precision of the descriptions of growth rather than overall accuracy. A special caveat to this generalization is relevant to my study. The precise quantitative outcomes of the analyses presented here are manifestations of the upper tails of the distributions of size at age. Better knowledge of Blue Marlin growth would undoubtedly improve details of the analyses. Improvements in methods and sampling could lead to such results; however, one wonders how it might be possible to quantify the size frequencies in the tails of the age distributions after they have been essentially altered (removed) by fishing. Similarly, I assumed the lengths of individuals were normally distributed about the means at age and sex, but the emergent population-size and catch-size distributions were skewed by the effects of mixing age compositions and mortality effects. At least for Atlantic Blue Marlin, nuances about the shapes of these distributions are factors that will not realistically be resolved by collecting additional samples with existing technology.

Although the specific NZ50 estimates here are for Atlantic Blue Marlin, most of the findings herein can be applied to other species with variations arising from similarities or differences with respect to the growth and mortality rates I used. The results here are strictly applicable to species that, once they become vulnerable to fishing, are then fished continuously throughout their subsequent lifespan. The basic findings should hold true even if strong age and size selective fishing applies, although fishing-induced increases in NZ50 may be meaningless if the sampled fishery is a prereproductive event for a semelparous species, as in many Pacific salmonids.

Explicit consideration of changes in the frequencies of the largest fish in the catch will often be a useful adjunct to the standard biomass and fishing biological reference points, B/B_{MSY} and F/F_{MSY}, now widely an ambition of stock assessment efforts. It should be possible to build distributions for test metrics based on sample sizes and observed maxima to allow for confidence statements about differences between maximum sizes in samples for different stock conditions. That effort was beyond the scope of this study. In addition to assessing the status of stocks already depleted by fishing, NZ50, or a similar measure could be a helpful metric for judging stock recovery. Landing limits implemented by management authorities can obfuscate estimates of changes in abundance based on catch or catch per unit effort. In many circumstances, the frequencies of the largest specimens in the catch will be more informative for judging stock recovery than are the average sizes, especially when catch restrictions limit landings of small fish (e.g., if minimum sizes are imposed). Specimens that were once rare events should become larger and more numerous as stocks rebuild from excessive fishing.

The fact that individual observations are chance events lessens the value of the maximum size in a sample as a biological reference parameter, displacing it in favor of a measure like NZ50, which is based on the cumulative fraction of observations in excess of some large threshold size. Nonetheless, the stochastic nature of observations can still be expected to undermine maximum-size criteria as the threshold is increased into the upper tail of the size distribution. Application of the concept explored here will require careful consideration of growth, mortality, and the selection of threshold values.

ACKNOWLEDGMENTS

REFERENCES

Anonymous. 2011. Report of the 2010 ICCAT Blue Marlin data preparatory meeting. Collective Volume Scientific Papers ICCAT 66:1554–1660.

Anonymous. 2012. Report of the 2011 Blue Marlin stock assessment and White Marlin data preparatory meeting. Collective Volume Scientific Papers ICCAT 68:1273–1386.

Boggs, C. H. 1989. Vital rate statistics for billfish stock assessment. Pages 225–233 *in* R. H. Stroud, editor. Planning the future of billfishes: research, and management in the 90's, and beyond. National Coalition for Marine Conservation, Marine Recreational Fisheries 13, Part 1, Savannah, Georgia.

Coble, D. W. 1988. Effects of angling on bluegill populations: management implications. North American Journal of Fisheries Management 8:277–283.

Cyr, E. C. 1987. Age, growth, and reproduction of Blue Marlin, *Makaira nigricans,* from South Carolina billfish tournament collections. Master's thesis. University of South Carolina, Columbia.

Goodyear, C. P. 1995. Mean size at age: an evaluation of sampling strategies using simulated red grouper data. Transactions of the American Fisheries Society 124:746–755.

Goodyear, C. P. 2003. Blue Marlin mean length: simulated response to increasing fishing mortality. Marine and Freshwater Research 54:401–408.

Goodyear, C. P., and F. Arocha. 2001. Size composition of blue and white marlins taken in selected fisheries in the Western North Atlantic. Collective Volume Scientific Papers ICCAT 53:249–257.

Hill, K. T., G. M. Cailliet, and R. L. Radtke. 1989. A comparative analysis of growth zones in four calcified-structures of Pacific Blue Marlin, *Makaira nigricans*. U.S. National Marine Fisheries Service Fishery Bulletin 87:829–843.

Kirkpatrick, M. 1984. Demographic models based on size, not age, for organisms with indeterminate growth. Ecology 65:1874–1884.

Prager, M. H., and C. P. Goodyear. 2001. Effects of mixed-metric data on production model estimation: simulation study of a Blue-Marlin-like stock. Transactions of the American Fisheries Society 130:927–939.

Prager, M. H., E. D. Prince, and D. W. Lee. 1995. Empirical length and weight conversion equations for Blue Marlin, White Marlin, and Sailfish from the North Atlantic Ocean. Bulletin of Marine Science 56:201–210.

Prince, E. D., D. W. Lee, J. R. Zweifel, and E. B. Brothers. 1991. Estimating age and growth of young Atlantic Blue Marlin *Makaira nigricans* from otolith microstructure. U.S. National Marine Fisheries Service Fishery Bulletin 89:441–459.

Seidensticker, E. P. 1996. Lake Nacogdoches, Texas: a case history of Largemouth Bass overharvest and recovery utilizing harvest regulations. Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies 48(1994):453–463.

Su, N. J., C. L. Sun, A. E. Punt, S. Z. Yeh, W. C. Chiang, Y. J. Chang, and H. Y. Chang. 2013. Effects of sexual dimorphism on population parameters and exploitation ratios of Blue Marlin (*Makaira nigricans*) in the northwest Pacific Ocean. Aquatic Living Resources 26:19–24.

Suzuki, Z. 2001. A note on the stock assessments results of the Fourth ICCAT billfish workshop held in Miami, Florida, July 18–28, 2000. Collective Volume Scientific Papers ICCAT 52:1522–1524.

Wilson, C. A. 1984. Age and growth aspects of the life history of billfishes. Doctoral dissertation. University of South Carolina, Columbia.

Wilson, C. A., J. M. Dean, E. D. Prince, and D. W. Lee. 1991. An examination of sexual dimorphism in Atlantic and Pacific Blue Marlin using body weight, sagittae weight, and age estimates. Journal of Experimental Marine Biology and Ecology 151:209–225.