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CAN CIRCLE HOOKS IMPROVE WESTERN ATLANTIC SAILFISH, *ISTIOPHORUS PLATYPTERUS*, POPULATIONS?

John F Walter, Eric S Orbesen, Christopher Liese, and Joseph E Serafy

ABSTRACT

Although many uncertainties surround the status of western Atlantic sailfish, *Istiophorus platypterus* (Shaw, 1792), stock size (B) is considered below and fishing mortality rate (F) above the targets that would allow maximum sustainable yield (MSY). One means of improving status is to implement live-release policies and to employ circle hooks to increase release survival. In the present study, we examined the efficacy of a switch to circle hooks to achieve population-level B_{MSY} and F_{MSY} targets. First, we evaluated the scope that exists to employ circle hooks and adopt live-release policies. Second, we decremented recent landings by the reductions that could be achieved through live release and increase in survival between circle hooks and traditional J-hooks. Third, we projected these landings in the Bayesian surplus production model. Assuming that landings in the non-release fleets remain constant, the current percentages of circle hooks (approximately 25%) and live release (approximately 25%) could reduce landings by 7%–8%. This measure alone would have less than a one percentage point increase in probability of improving status. With maximum practicable live release of around 50%, because many fleets market sailfish, and 100% circle hook use, landings could be reduced by 13%–23%. This would only have a 0.42–1.36 and 0.45–2.56 percentage point increase in the probability of meeting biomass and fishing mortality targets, respectively. While circle hooks can be a useful tool to convert landed fish to live releases, they are unlikely to meet current targets for western Atlantic sailfish unless combined with other management that would reduce overall landings.

The movement to use circle hooks in many fisheries is motivated by the notion that it will have positive, population-level impacts for target and/or non-target species. Numerous studies indicate that replacing traditional J-hooks with circle hooks can increase the probabilities of survival and reduce deep-hooking (Cooke and Suski 2004). But determining whether such a switch will result in benefits to populations requires use of a population model that balances the benefits against other known sources of mortality and adequately captures the population dynamics of growth, mortality, and reproduction.

For istiophorid billfishes, there is a general pattern of increased probability of surviving the hooking process with circle hooks (Serafy et al. 2009) both in recreational (Prince et al. 2002, Horodysky and Graves 2005) and commercial longline fisheries (Diaz 2008, Kerstetter and Graves 2008). This can be modeled as increased release survival, even if, in some cases, survival after release does not differ between hook types, but the probability of being alive at gear haulback does so the fish can be released. For sailfish, *Istiophorus platypterus* (Shaw, 1792), Serafy et al. (2012a) found a 20 percentage point (from 41% to 61%) increase in the probability of being

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alive at gear haulback of before vs after the implementation of a mandatory circle hook requirement in the United States pelagic longline fishery. In the same fishery, Kerstetter and Graves (2006) found that 18/0 circle hooks increased the probability that a fish was alive at boatside from 57.2% to 85.7% over traditional J-hooks. In a series of alternating-hook longline experiments, Watson et al. (2005) noted that circle hooks increased the probability of fish being alive at haulback for many other pelagic species over J-hooks, but that the effects varied by hook offset, size, and bait. There are mechanistic reasons for increased survival, which appear to be due to a tendency for circle hooks to lodge in the mouth or jaw rather than in critical internal tissues (Cooke and Suski 2004), leading to a higher probability of release survival.

Variability in the observed magnitude of increased survival, combined with the lack of a standard definition of what constitutes a circle hook (though see Serafy et al. 2012b), complicates quantifying the realized impact of a fleet-level switch from J-hooks to circle hooks. Differences in bait type, rigging, and fishing practice and particularly in the size, offset, and model of circle hook can alter their effects (Watson et al. 2005). Furthermore, unidentifiable spatial, environmental, or operational factors appear to lead to differences in circle hook effects (Serafy et al. 2012a). In the two fisheries that have moved from J-hooks to circle hooks, the United States pelagic longline fishery and the Brazilian high seas longline fishery, the standards for what constitutes a circle hook, provide latitude for employing different hook shapes, degrees of offset, and manufacturers. For the US longline fishery, the primary circle hook specification was a temporal and spatial requirement that non-offset 18/0 circle hooks be used in some areas to reduce sea turtle bycatch (NMFS 2004), though current regulations now require a "weak" hook in the Gulf of Mexico (NMFS 2011). In practice, any voluntary or regulatory shift to circle hooks in other fleets is likely to result in a mix of various circle hook types and sizes, bait combinations, rigging options, and fishing practices. This makes obtaining a single point estimate of the effect of circle hooks difficult. For this reason, we use a range of circle hook effects on fish survival derived from Serafy et al. (2012a) and Kerstetter and Graves (2006).

To realize the full benefits of circle hooks, two other conditions must also occur. First, there must not be a substantial increase in catch rates of bycatch species that might increase the number of fish encountering the gear or a substantial decrease in catch rate of target species that might increase total effort. Serafy et al. (2009) performed a quantitive review of studies focusing on istiophorids that compared J-hook vs circle hook performance. Of the seven studies that compared catch rates, none found (statistically) significant differences between the two hook types.

The second required condition is that the fisheries that switch to circle hooks (longline, handline, rod-and-reel fisheries) must release live fish (Kerstetter and Graves 2008). Much of the recreational fishery in the western Atlantic already follows a release policy for billfish and has widespread circle hook utilization (Peel et al. 2003), such that the scope for further recreational circle hook benefits is limited. In contrast, longline fleets comprise approximately 66% of the total western Atlantic sailfish, landings and many do not target or market sailfish, so there is substantial theoretically scope for commercial circle hook adoption effects. Furthermore, since 1988, US Atlantic longliners have been prohibited from selling sailfish (effectively making their release mandatory) and have been required to use circle hooks since 2004. Brazilian longliners are also encouraged to practice live release and have been in the process of adopting circle hooks (Kerstetter et al. 2006). In the numerous artisanal handline and longline fisheries, sailfish remain a marketed species, making universal adoption of live release policies unlikely. Thus, the primary target for further benefits in the western Atlantic involves the non-artisanal longline fleets.

Here we examine the population-level benefits that might accrue as a result of an increase in release survival afforded by a switch to circle hooks for commercial fisheries capturing western Atlantic sailfish. The overall approach of this modeling exercise was to evaluate International Commission for the Conservation of Atlantic Tunas (ICCAT) landings databases by fleet, gear, and fishery to determine the scope for impact of circle hooks as determined by the fraction of landings from hook-based fleets that would release sailfish. We use a matrix derived from a range of percent live release and circle hook usage and plausible increases in survival obtained from empirical and experimental studies to decrement the present mean landings. Finally, to determine the potential for circle hooks to meet biomass and fishing mortality rate targets, the resulting reduced landings are used to project the population forward in time using one of the most recent ICCAT stock assessment models.

Methods

Stock Assessment and Management.—Atlantic sailfish stock assessment and management is one of the charges of ICCAT (Restrepo et al. 2003). The most recent assessment indicates that western Atlantic sailfish is possibly, and eastern sailfish is likely, overfished and undergoing overfishing (ICCAT 2010). Largely on the basis of tagging data showing no trans-oceanic movements (Ortiz et al. 2003, Orbesen et al. 2008), sailfish are classified into eastern and western Atlantic stocks (Fig. 1) and separate assessment models are constructed for each. The scarcity of age and length composition and other biological data available for sailfish limited the assessment to surplus production models (SPMs) that require only landings and catch per unit effort (CPUE) indices (Prager 1994).

SPMs generally only estimate three parameters: r, the intrinsic rate of population growth; K, the carrying capacity of the stock; and survey catchability, a scalar that relates CPUE to abundance. The parameters r and K describe the population dynamics of the species and determine critical management benchmarks: MSY (maximum sustainable yield) = $rK/4$; F_{MSY} (fishing mortality rate at MSY) = $r/2$, and B_{MSY} (biomass at MSY) = $K/2$, for a symmetric Schaefer production model (Schaefer 1957). While SPMs cannot capture complex age-structured biology, they often provide reliable management advice in the absence of data to inform these processes (Prager 1994).

In practice, there is often insufficient information to reliably estimate r and K; however, life-history theory or prior knowledge can often provide plausible values for these parameters (McAllister et al. 2001). For example, a species with an extremely fast growth rate, short life span, and high fecundity would likely have a high value of r (and conversely a lower value of K) compared to another species. Bayesian estimation methods provide a statistical framework for incorporating known information in the form of prior distributions for parameters and can provide model solutions in data-poor situations (McAllister et al. 2001).

The ICCAT sailfish stock assessment used several different SPMs, but only a Bayesian surplus production (BSP) model (Andrade and Kinas 2007) will be used in this exercise as it captures much of the range of uncertainty of the other models and it was readily modified for projections. Two BSP models were used for advice in the 2009 assessment, one with an informative, or narrow, prior distribution for r and K, and one with an uninformative, or wide, prior distribution (ICCAT 2010). Narrow priors exert a stronger influence on the value of the posterior estimate and are used when there is greater prior knowledge of a particular parameter value (Gelman et al. 1995). The posterior estimates of r from the BSP models spanned a range of high (posterior median r = 0.154) and low (posterior median r = 0.09) stock

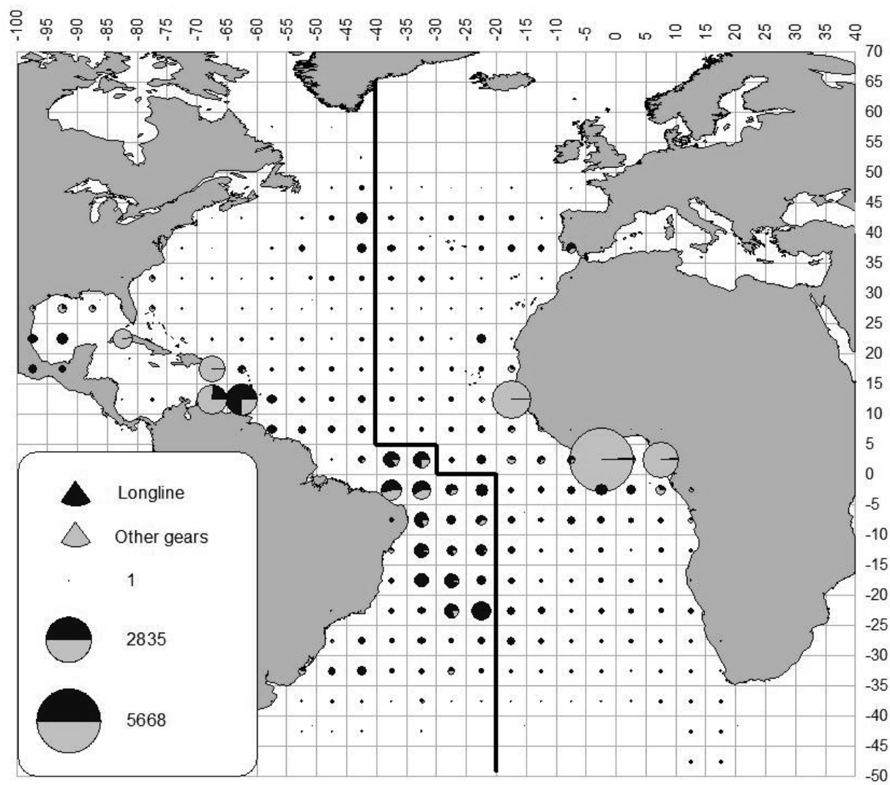

Figure 1. Map of distribution of Atlantic sailfish catches by gear type. Other gear types include surface gillnets, purse seine, handline, and rod and reel. Numbers represent metric tons and circles are proportion to landings. The dark line represents the partitioning between East and West. Figure reprinted from ICCAT (2010) with permission.

productivity which differ slightly from those reported in the ICCAT (2010) stock assessment as we had to re-run the models to obtain the posterior estimates. As each of the posterior estimates provides a separate r and K value, they translate uncertainty in the estimation of the productivity to the projections.

SPMs do not explicitly incorporate release mortality. Therefore, to incorporate the effect of circle hooks, we reduced landings according to expected benefits from circle hooks. With the exception of the US and Brazilian longline fleets, any benefit from circle hooks would occur in the future and would be part of population projections. Thus, by decrementing future landings according to the fraction of live releases and proportion of circle hook use and projecting the population forward, it was possible to assess the future status under various scenarios.

Landings and Scope for Circle Hook Impacts.—For the purposes of these analyses, we adopt the ICCAT convention that reported landings (Table 1) represent total removals (landed fish plus dead discards). For western Atlantic sailfish, approximately 66% of the landings derive from hook-based (longline, handline, and rod and reel) fisheries, thus changing hook types could confer population benefits (Fig. 1, Table 1). Historically there have been substantial recreational landings of sailfish in the western Atlantic (approximately 30%–40% of the total from 1980 to 1995). However, most of this fishery has become catch and release with apparently very few dead discards as evidenced by the reduction in rod-and-reel landings reported to ICCAT (Table 1). Furthermore, much of this fleet has already voluntarily adopted circle hooks. Hand-line landings are minor, such that any changes in these fishing practices

Table 1. ICCAT landings of western Atlantic sailfish, *Istiophorus platypterus*, in metric tons.

Year	Gill net	Hand line	Long line	Rod and reel, sport	Surface	Trawl	Unknown	Total	Fraction longline
1988			391	472	54		154	1,071	37%
1989			373	352	45		193	963	39%
1990			379	267	226		288	1,160	33%
1991	41		223	371	32		448	1,115	20%
1992	25		393	333	133		441	1,325	30%
1993	60		547	233	71		367	1,278	43%
1994	65		374	217	131		272	1,059	35%
1995	41		367	348	183		186	1,124	33%
1996	98		329	230	264		120	1,041	32%
1997	114		380	350	168		151	1,163	33%
1998	182		526	267	167		204	1,346	39%
1999	140		604	163	105		370	1,382	44%
2000	71		845	76	134		397	1,523	55%
2001	64	3	989	58	81	2	255	1,451	68%
2002	88	3	1,272	103	260		255	1,981	64%
2003	93	0.1	876	0.18	91	0.3	256	1,316	67%
2004	122		754	0.24	470	1	50	1,396	54%
2005	131		1,066	0.41	165		72	1,435	74%
2006	135	2	652	0.34	133	1	105	1,028	63%
2007	186	1	691	5	147	3	116	1,149	60%
2008	113	4	984	4		4	150	1,258	78%
2009	96	2	952	3	0.05	1	361	1,415	67%
Mean 2000–2009	110	2	908	25	165	2	202	1,395	65%

would have limited impact. Pelagic longline fisheries (approximately 99% of the landings from hook-based fleets) represent the greatest scope for circle hook impact. Most longline landings also come from non-artisanal fleets that do not market sailfish, increasing the potential for live release. Substantial landings remain in the surface and unknown fishery categories which could also be captured with hook gear. However, it is likely that these fleets market sailfish. In contrast, eastern Atlantic sailfish are primarily captured in pelagic gillnet and purse seine operations with minor landings from artisanal handlines and high seas longlines (Fig. 1). Much of the catch is marketed, so the potential for release is low and since longline caught fish represent <10% of the total removals, the scope for benefits of circle hook implementation is even lower. For this reason, we only evaluate the western Atlantic stock.

Decrementing Landings.—To decrement total landings, we used the adjusted survival probability (S) as a weighted mean of survival with and without circle hooks:

$$S = (\%C) * (S_b + S_{inc}) + (1 - \%C) * S_b \qquad \text{(Eq. 1)}$$

This equation reduces to $S = S_b + \%C * S_{inc}$, where S is the adjusted survival probability, S_b is baseline survival, assumed to be 41% (Serafy et al. 2012), S_{inc} is the increase in survival due to circle hooks and $\%C$ is the percentage of circle hooks used (Table 2).

To obtain the reduction in landings, we adjusted the mean longline landings for 2000–2009 (Table 1) by the reductions that could accrue from live release and circle hooks as follows:

Table 2. Adjusted release survival (S) as a weighted mean of survival with circle hooks and baseline survival ($S_b = 0.41$) for different levels of circle hook use and different levels of increase in survival due to circle hooks.

	Percentage point increase in survival with circle hooks				
Circle hook use	0%	10%	15%	20%	30%
0%	41	41	41	41	41
25%	41	44	45	46	49
50%	41	46	49	51	56
75%	41	49	52	56	64
100%	41	51	56	61	71

$$\text{Reduced longline landings} = (1 - S * \%R) * \text{mean longline landings} \qquad \text{(Eq. 2)}$$

where $\%R$ is the percent of live release. Next, these reduced landings were added to the sum from other sources to obtain the fractional reductions in total landings that would occur with different levels of % release, % circle hook use, and increase in survival (Table 3). These fractions were then multiplied by landings of 1500 t under the assumption that landings in the kill (non-release) fleets would remain the same, but that the reductions would apply for the release fleets (Table 4).

We started with a level of landings (1500 t) approximating the mean of 2000–2005 to reflect the recent baseline level of landings (retained sailfish catch and dead discards) prior to the use of circle hooks in most fleets except the United States (Table 1). This time period was prior to the initiation of circle hooks in the Brazilian fleets. Since 2005, reductions in reported landings from fleets that release sailfish have reduced the 2000–2009 mean total landings to 1395 t, which largely reflects that about 25% of the fleets now practice live release (Table 4).

Population Projections.—The 2009 ICCAT stock assessment for sailfish contained data through 2008. To evaluate the impact of future scenarios, we modified the assessment model code to project the population forward in time beginning in 2009. We projected the western

Table 3. Total landings as percent of baseline landings for different levels of sailfish release, circle hook use, and increase in survival due to circle hooks. [Percent of total landings that remain = (longline landings as reduced by circle hook use + other landings) / baseline landings].

		Percentage point increase in survival with circle hooks				
Release	Circle hook use	0%	10%	15%	20%	30%
25%	0%	93.3	93.3	93.3	93.3	93.3
25%	25%	93.3	92.9	92.7	92.5	92.1
25%	50%	93.3	92.5	92.1	91.7	90.9
25%	75%	93.3	92.1	91.5	90.9	89.7
25%	100%	93.3	91.7	90.9	90.1	88.4
50%	0%	86.7	86.7	86.7	86.7	86.7
50%	25%	86.7	85.8	85.4	85.0	84.2
50%	50%	86.7	85.0	84.2	83.4	81.8
50%	75%	86.7	84.2	83.0	81.8	79.3
50%	100%	86.7	83.4	81.8	80.2	76.9
100%	0%	73.3	73.3	73.3	73.3	73.3
100%	25%	73.3	71.7	70.9	70.1	68.4
100%	50%	73.3	70.1	68.4	66.8	63.6
100%	75%	73.3	68.4	66.0	63.6	58.7
100%	100%	73.3	66.8	63.6	60.3	53.8

Table 4. Total landings in metric tons for different levels of sailfish release, different levels of circle hook use, and different levels of increase in survival due to circle hooks. Landings reduced from an initial, baseline level of 1500 t.

		Percentage point increase in survival with circle hooks				
Release	Circle hook use	0%	10%	15%	20%	30%
25%	0%	1,400	1,400	1,400	1,400	1,400
25%	25%	1,400	1,394	1,391	1,388	1,382
25%	50%	1,400	1,388	1,382	1,376	1,363
25%	75%	1,400	1,382	1,372	1,363	1,345
25%	100%	1,400	1,376	1,363	1,351	1,327
50%	0%	1,300	1,300	1,300	1,300	1,300
50%	25%	1,300	1,288	1,282	1,275	1,263
50%	50%	1,300	1,275	1,263	1,251	1,227
50%	75%	1,300	1,263	1,245	1,227	1,190
50%	100%	1,300	1,251	1,227	1,202	1,153
100%	0%	1,100	1,100	1,100	1,100	1,100
100%	25%	1,100	1,075	1,063	1,051	1,027
100%	50%	1,100	1,051	1,027	1,002	953
100%	75%	1,100	1,027	990	953	880
100%	100%	1,100	1,002	953	905	807

Atlantic sailfish population assessments into the future assuming that overall effort will be similar to that which has produced recent mean landings with no changes in the allocation of landings by fleet and gear. Present ICCAT regulations do not limit fishing effort or landings of sailfish. Currently we estimate that approximately 25% of the longline landings come from fleets that have mandatory live release of sailfish including United States (NMFS 2004) and Brazil (F Hazin, Universidade Federal Rural de Pernambuco, pers comm, 2011).

Projection of the posterior estimates of r and K provided stochasticity in stock productivity. This allowed calculation of the probabilities of ending overfishing [Prob($F < F_{MSY}$)] and of rebuilding the stock from an overfished condition [Prob($SSB > SSB_{MSY}$)] under various levels of landings. We use a 10-yr rebuilding timeframe and evaluated the Prob($SSB > SSB_{MSY}$) in 2018, 10 yrs after the final year model.

Modeling Assumptions.—The primary assumptions of this modeling exercise were: (1) the two Bayesian production models for western Atlantic Sailfish span ranges of stock productivity; (2) the "circle hook effect" is an increase in the percent of fish alive at retrieval; (3) changing to circle hooks will not change catchability or age-specific vulnerability and hence will not change MSY-related benchmarks; (4) the "no release" fleets will maintain landings similar to the 2000–2009 mean and reductions will come from the release fleets (we examine different total landings in sensitivity analyses); (5) baseline survival of sailfish from longline capture is 41% (Serafy et al. 2012), which we further examined through sensitivity analyses. Our method also assumed that all live released fish survive with no post-release mortality, though the above sensitivity analysis can be used interchangeably to evaluate changes in baseline or post-release survival; and (6) because we decremented the landings in metric tons, rather than converting landings for each fleet into numbers, we assume that the mean fish sizes captured by each fleet are similar (approximately 160 cm lower jaw fork length, ICCAT 2010).

Sensitivity Analyses.—We tested the sensitivity of the results to a different baseline survival rate, ranging from 30% to 60%. To evaluate the impact of different levels of assumed total landings, we projected a range from 500 to 2500 t.

Table 5. Percentage point increase in probability of ending overfishing for different levels of sailfish release, different levels of circle hook use, and different levels of increase in survival due to circle hooks [Prob($F < F_{msy}$)].

		Percentage point increase in survival with circle hooks				
Release	Circle hook use	0%	10%	15%	20%	30%
25%	0%	0.10	0.10	0.10	0.10	0.10
25%	25%	0.10	0.10	0.10	0.10	0.13
25%	50%	0.10	0.10	0.13	0.13	0.16
25%	75%	0.10	0.13	0.13	0.16	0.19
25%	100%	0.10	0.13	0.16	0.16	0.29
50%	0%	0.45	0.45	0.45	0.45	0.45
50%	25%	0.45	0.52	0.52	0.58	0.65
50%	50%	0.45	0.58	0.65	0.75	1.17
50%	75%	0.45	0.65	0.75	1.17	1.55
50%	100%	0.45	0.75	1.17	1.39	2.56
100%	0%	4.60	4.60	4.60	4.60	4.60
100%	25%	4.60	5.83	6.67	7.84	10.53
100%	50%	4.60	7.84	10.53	13.93	22.87
100%	75%	4.60	10.53	15.94	22.87	37.84
100%	100%	4.60	13.93	22.87	32.59	53.19

Results

According to our calculations, landings could be reduced to between 53.8.% and 93.3% (Table 3) of the assumed baseline of 1500 t or between 807 and 1400 t (Table 4). Assuming that the present level of circle hook utilization and release produces landings of approximately 1400 t, varying levels of circle hook adoption coupled with sailfish release by 50% of the longline fleets could further reduce total landings by 7%–16% (Table 4). For comparison, the estimated mean and 5th and 95th percentile of MSY values from the Bayesian surplus production models was 734 (396–1053) t for the low productivity model and 891 (605–1119) t for the high productivity model. Thus, most of the reductions were still substantially higher than MSY estimates from models.

Projecting this matrix of landings forward in time immediately changes the probability of ending overfishing Prob($F < F_{MSY}$), as any reduction in landings below F_{MSY} ends overfishing (Table 5). These and all subsequent results represent means across both assessment models. The greatest potential to end overfishing results from changes in live release, a necessary condition for any "circle hook effect." Each of the three levels of live release (25%, 50%, and 100%) evaluated have substantially higher baseline probabilities of reaching management targets (Table 5), though generally only at 100% live release, ≥50% circle hook use, and ≥15 percentage point increased survival was the probability of ending overfishing >10%, indicating that circle hooks and live release are unlikely to be sufficient in ending overfishing in isolation of other measures.

Subtracting from a baseline of zero circle hook usage isolates the effect of circle hooks in ending overfishing (Fig. 2A). In this case, we show only the current situation of 50% live release; higher or lower levels of live release scale these effects. Increases

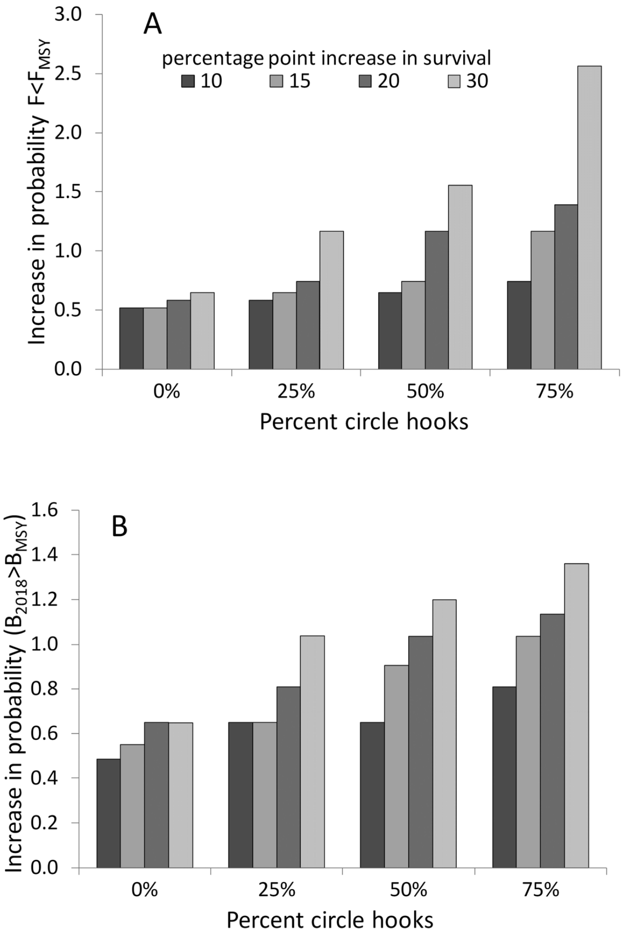

Figure 2. Increase in probability of (A) $F < F_{MSY}$ and (B) $B_{2018} > B_{MSY}$ given 50% live release for different levels circle hook use and different levels of increase in survival. These values represent increases from the situation of no circle hook usage and are intended to show the scope for increase in probabilities with increasing circle hook usage.

in the potential to reduce overfishing are low (0.52–2.56 percentage points) and increase linearly with the percentage of circle hook usage for all levels of circle hook effect. For 25% and 100% live release (not shown), increases range from 0.1 to 0.29 and 5.8 to 53.2 percentage points, respectively, indicating much greater potential for circle hook impacts with higher levels of live release.

Similarly, the baseline probabilities of rebuilding the stock by 2018 [Prob($SSB_{2018} > SSB_{MSY}$)] was affected by the absolute levels of live release (Table 6). However, at any level, these probabilities were lower than the probabilities of ending overfishing. This indicates that even if overfishing were ended, reducing catch levels down to or below those at F_{MSY} would be unlikely to rebuild the stock by 2018. At the highest level of live release, circle hook effect, and percent usage, there was only a 5.7 percentage point increase in the probability of rebuilding the stock and, at more attainable levels of 50% live release, the maximum increase was only 1.36 percentage points.

Table 6. Percentage point increase in probability of stock recovery by 2018 for different levels of western Atlantic sailfish release, different levels of circle hook use, and different levels of increase in survival due to circle hooks [Prob($B_{2018} > B_{MSY}$)].

		Percentage point increase in survival with circle hooks				
Release	Circle hook use	0%	10%	15%	20%	30%
25%	0%	0.13	0.13	0.13	0.13	0.13
25%	25%	0.13	0.16	0.19	0.19	0.19
25%	50%	0.13	0.19	0.19	0.19	0.19
25%	75%	0.13	0.19	0.19	0.19	0.29
25%	100%	0.13	0.19	0.19	0.29	0.36
50%	0%	0.42	0.42	0.42	0.42	0.42
50%	25%	0.42	0.49	0.55	0.65	0.65
50%	50%	0.42	0.65	0.65	0.81	1.04
50%	75%	0.42	0.65	0.91	1.04	1.20
50%	100%	0.42	0.81	1.04	1.13	1.36
100%	0%	1.65	1.65	1.65	1.65	1.65
100%	25%	1.65	2.01	2.01	2.14	2.43
100%	50%	1.65	2.14	2.43	2.82	3.50
100%	75%	1.65	2.43	2.88	3.50	4.34
100%	100%	1.65	2.82	3.50	4.08	5.67

Isolating the circle hook effect indicates that the increase in probability of rebuilding the stock was linearly related to both the increase in the percent of circle hooks used and the increase in the circle hook effect on survival (Fig. 2B). Results are shown only for the 50% live release, but scale similarly with increased or decreased percentage of live release.

Sensitivity Analyses.—Adjusting the baseline survival rate from 30% to 65% changes the absolute magnitude of the potential benefits, but has very little influence on the effect that circle hooks alone would contribute (Fig. 3). This is because the effect of circle hooks is additive to the baseline survival rate, and so increasing baseline survival only means that there is increased overall survival, which increases the probability of meeting management objectives. Subsequent post-release mortality would, in the model, have the effect of reducing the baseline survival and, to the extent of this mortality rate, reduce the probabilities of meeting management objectives.

Changing the projected absolute level of landings has a substantial impact on the scope for circle hook benefits, as measured by the probability of ending overfishing [Prob($F < F_{MSY}$), Fig. 4] and rebuilding the stock by 2018 (not shown, but the figure is similar). The scope for benefits is greatest at intermediate landing levels of 500–1000 t, which bracket the MSY values from the BSP models. Higher landings result in relatively little scope because they are higher than most estimates of MSY and are not predicted to rebuild the stock, regardless of the level of circle hook utilization. Similarly, landings ≤500 t are lower than most estimates of MSY and result in an immediate end to overfishing and almost always rebuilds the stock by 2018.

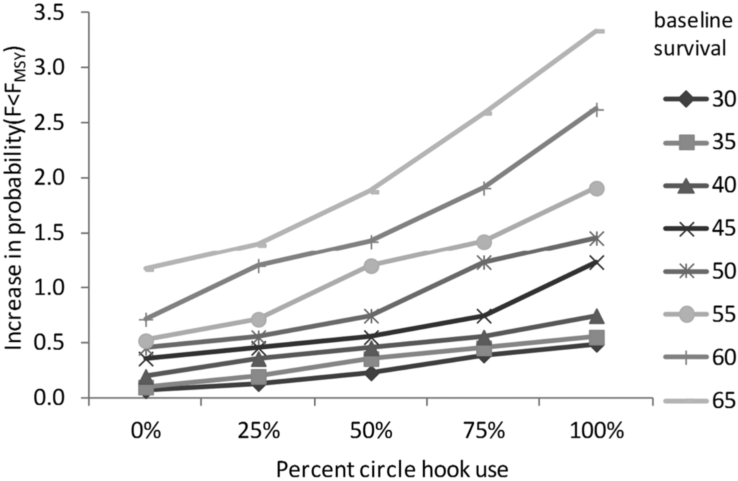

Figure 3. Effect of changing the baseline survival rate on the probability of ending overfishing given 50% live release and 20 percentage point increase in survival. The figure for the probability of rebuilding is similar but not shown.

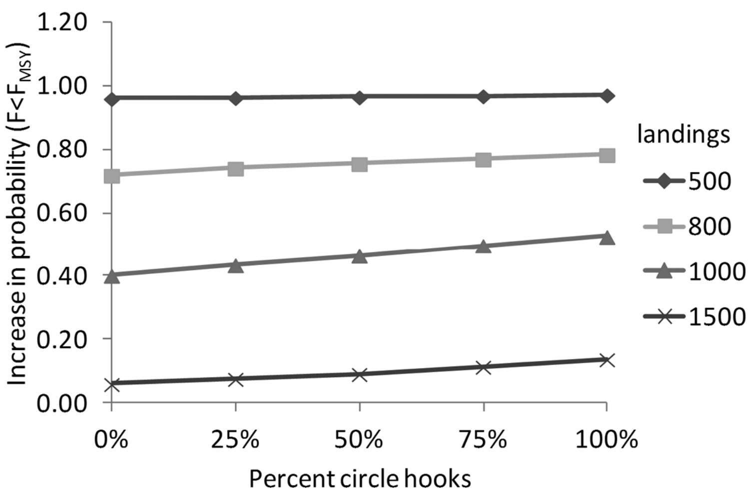

Figure 4. Effect of changing the absolute level of removals on the probability of ending overfishing given 50% live release and 20 percentage point increase in survival. The figure for the probability of rebuilding is similar, but not shown.

Discussion

This analysis provides a range of scenarios for circle hooks to meet the management objectives of rebuilding the stock to B_{MSY} and reducing fishing mortality to less than F_{MSY} for western Atlantic sailfish. While substantial reductions in total landings (likely between 7% and 23%) could be achieved through use of circle hooks and live release, these were generally not enough to meet management objectives in isolation of other measures that might reduce total landings. The possibilities range from the current situation where there are negligible population-level benefits to a maximum, albeit unlikely, situation where all longliners switch to circle hooks, circle hooks increase post-release survival from 41% to a maximum of 71% (30 percentage point increase), and all of the fleets that fish with hooks practice live release. In this case, current total removals could be reduced to around 807 t, which is within the estimates of MSY from the two assessment models (734–890 t; ICCAT 2010). These results differ from those of Kerstetter and Graves (2008) primarily because they evaluated the potential that all fleets would implement a live release policy, which could reduce total removals down to the 600 t replacement yield estimated in 2001 (ICCAT 2002). In contrast, we assumed that only the recreational and larger longline fleets would release fish and not the gillnet and artisanal handline and smaller longline fleets that, to our knowledge, market the fish, hence the total scope for reductions in removals is less in our study.

In practice, many fleets are unlikely to switch to circle hooks for a variety of reasons related to perceived reductions in target species catch rate (Falterman and Graves 2002) or simply fishers' preference for a certain hook type, such as the Japanese style "tuna hooks" (Yamaguchi 1989). Furthermore, many fleets are unlikely to abandon their market for sailfish and adopt a live-release policy. Thus, the most plausible range of potential benefits would likely be somewhere in the middle, where about half of the longline fleets switch to circle hooks and practice release of sailfish. Under this scenario the increase in survival of 15 percentage points would increase the potential to meet biomass and fishing mortality rate objectives by only about one percentage point, assuming the reductions in landings in the release fleets were not reallocated to the "kill fleets."

These very modest gains demonstrate that the most critical factor determining the potential for positive circle hook effect is adequate scope for benefits, which means that there are landings that could be converted to live releases and fleets that might be willing to implement circle hooks. The absolute effect of circle hooks on increased survival, whether it is 10%, 15%, 20%, or 30% is less critical and unlikely to be a single value in practice due to variations in hook type and utilization among vessels. For the eastern Atlantic, limited scope exists for circle hooks to benefit the population as most of the fish are captured by non-hook gear and are marketed. However, for the western Atlantic, there is substantial scope, but under the most plausible scenarios, it is unlikely that circle hooks can achieve objectives *in isolation* of other management measures.

These results are the product of several assumptions which require some comment. The primary assumption of this modeling exercise relative to the potential to meet MSY-related management objectives is that the two Bayesian production models span ranges of biological plausibility. While no production model was particularly well-determined in the 2009 stock assessment, the estimated r values of the models deemed acceptable for management advice ranged from 0.064 to 0.31 (median = 0.134), placing the values used in this analysis well within this range (ICCAT 2010). Carruthers and McAllister (2011) also estimated similar r values for sailfish, and the low (0.09) and high (0.15) median posterior estimates place sailfish among the least productive of all fishes in suborder scombroidei under ICCAT jurisdiction. If these low productivity estimates are accurate, it is unlikely that the calculated reductions in landings could substantially improve stock status.

There are also substantial uncertainties in the sailfish assessment, which include species misidentification, unreported and unregulated landings, uncertain stock structure, and highly variable CPUE indices (Restrepo et al. 2003). All of these factors affect estimation of r and K values, which directly determine the magnitude of the potential improvement in stock status afforded by circle hooks and live release. For production models, the most critical of these assumptions is that the landings accurately reflect total killed fish, which might not be the case with substantial discarding (Hammond and Trenkel 2005). Given the substantial decline in landings in the sport fishery, which presumably is due to released fish, it seems likely that there may be some unaccounted discard mortality. The effects of this unaccounted mortality would undoubtedly influence the model estimates of stock productivity (Koonce and Shuter 1987). If the CPUE indices are unaffected, then underestimation of historical removals in production models generally leads to underestimates of stock productivity as the model interprets the same CPUE trends as having occurred with even more fish removed from the population. Such a bias could lead to underestimates of r and K, which in turn would lead to underestimates of the scope for circle hook benefits in this analysis.

This modeling exercise also assumes that there will be no change in the age-specific vulnerability of the population and that multi-species interactions will not alter the potential benefits of circle hooks. The paucity of data for sailfish precluded ICCAT from conducting a more detailed age- and fleet- structured assessment for sailfish. When considered in an ecosystem context, circle hooks may have indirect impacts on a species by altering the mortality or catchability of predators or prey (Kaplan et al. 2007); however, multispecies interactions are beyond the scope of the present study and well beyond the modeling supported by ICCAT assessments. Provided more fleets adopt live-release policies, future ICCAT assessments may need to incorporate more detailed population models that could allow for more realistic modeling of harvest control strategies (Koonce and Shuter 1987).

The last major assumption warranting comment is that landings and relative allocation of landings by fleets and gears will remain similar to the 2000-2009 average. The 10-yr projections fail to capture the reality that, as the stock rebuilds, catch rates for all fleets will likely increase with increasing abundance, leading to increased landings in the kill (non-release) fleets. This issue is most problematic because maintaining constant landings assumed in the projections requires quotas in the kill fleets, which currently do not exist. Furthermore, nothing in the current management of Atlantic sailfish prohibits the reallocation of landings to fleets that do not release fish or would not use circle hooks thereby undermining conservation benefits obtained by fleets that release sailfish or use circle hooks. While it is not the purpose of the present study to evaluate the fishing practices of specific fleets, the potential for reallocation to fleets that market sailfish poses a problem for the overall management of sailfish.

In conclusion, while circle hooks appear to have conservation benefits for sailfish, their efficacy as a management measure for stock-wide benefits is predicated upon adoption and adherence to live-release policies and that reductions in landings are not simply reallocated to fleets that harvest sailfish. In the most plausible scenarios, circle hooks and voluntary live release will likely not be sufficient measures and reductions in total landings, and limits on transfer of landings from the release fleets to the kill fleets, would still be necessary to meet management objectives relative to MSY. Nonetheless, management measures for pelagic species can have benefits in increased local abundance (Jensen et al. 2010) as Atlantic sailfish exhibit more restricted movements (Jolley and Irby 1979, Ortiz et al. 2003, Kerstetter and Graves 2008) than other billfishes. That circle hook use alone cannot meet management objectives reflects the dual, competing uses of sailfish (Peel et al. 2003). For some fleets, sailfish are valued for meat and are unlikely to be released. In this case, management measures aimed at reducing or limiting total landings, as is used for tunas, are necessary even if many fleets voluntarily adopt live release and circle hooks. For other fleets, where sailfish are not marketed, further live release policies and circle hook adoption can confer minor population level benefits.

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Address: *US National Marine Fisheries Service, Southeast Fisheries Science Center, 75 Virginia Beach Drive, Miami, Florida 33149.* Corresponding Author: (JFW) *Email: <john.f.walter@noaa.gov>, Telephone: 305-361-4255.*