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Can circle hook use benefit billfishes?

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Abstract

We performed a quantitative review to evaluate circle hook use in recreational and commercial hook-and-line fisheries that interact with billfishes (Family: Istiophoridae). Specifically, we scrutinized the findings of 11 recent empirical studies that reported, on a species-specific basis, side-by-side measures of circle vs. J-hook fishing performance: catch, mortality, deep-hooking and bleeding rates. Of the 30 total comparisons extracted from the literature that satisfied our inclusion criteria, 13 indicated significant differences between hook types for the specific metric compared. No study reported significant billfish catch rate differences between hook types. However, when significant differences between hook types were found, higher mortality rates and higher rates of deep-hooking and bleeding were associated with J-hooks relative to circle hooks. We conclude that empirical evidence is sufficient to promote circle hook use in almost all hook-and-line fishery sectors that typically interact with istiophorids. However, billfish conservation benefits will only be realized if fishers use unmodified circle hooks, commit to releasing live fish and take other appropriate measures which maximize post-release survival. While there may be fishing modes where circle hook effects are negative, for billfish conservation, we recommend managers grant exceptions to circle hook use only when experimental results support such a practice.

Keywords Billfish, circle hooks, hook performance, marlin, sailfish, review

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Introduction

The billfishes (Family Istiophoridae: marlins, sailfish and spearfishes) are apex predators in subtropical and tropical pelagic waters around the globe. The marlins and sailfish support recreational fisheries that have been valued in billions of dollars (Ditton and Stoll 1998). All of the istiophorids are caught as bycatch in pelagic longline fisheries where, in some cases, they are retained for consumption. There is general consensus that the pelagic longline fisheries targeting tunas (Scombridae) and swordfish (*Xiphias gladius*, Xiphiidae) are the principal source of adult istiophorid mortality, although recreational fisheries may also contribute significantly to fishing mortality on billfish species in US waters (see Cramer 2004; Kerstetter and Graves 2006a). Stock assessments of the Atlantic billfishes indicate that populations of blue marlin (*Makaira nigricans*), white marlin (*Tetrapturus albidus*) and to a lesser extent sailfish (*Istiophorus platypterus*) are well under the levels supporting maximum sustainable yields (ICCAT 2007). Past stock assessments of Indo-Pacific billfish stocks suggest that populations of blue marlin, black marlin (*Makaira indica*) and striped marlin (*Tetrapturus audax*) are at levels near maximum sustainable yield (Uozumi 2003). The stock status of the spearfishes (longbill spearfish *Tetrapterus pfluegeri*, roundscale spearfish *Tetrapterus georgii*, Mediterranean spearfish *Tetrapterus belone* and shortbill spearfish *Tetrapterus angustirostris*) and Indo-Pacific sailfish is unknown. If the populations of the species targeted by the pelagic longline fisheries are sustainable, but populations of bycatch species are low, the management challenge is to identify means to protect the bycatch without adversely affecting target catches.

Several types of hooks are currently in use by commercial and recreational pelagic fisheries, including circle hooks, J-hooks and the so-called 'tuna hooks' (Fig. 1). Circle hooks were originally developed in the Pacific Ocean (Hurum 1977; Johannes 1981) and differ from conventional J-hooks in their general shape and in the orientation of the point with respect to the shank. In the former, the shape is rounded and the point tends to be oriented perpendicular to the shank; in contrast, a J-hook is shaped as its name implies, with its point oriented parallel to the hook shaft. The tuna hook is somewhat intermediate and used in some pelagic longline fleets targeting the large tunas. While the tuna hook shaft is neither completely straight nor completely perpendicular to the point, it has been categorized as a type of J-hook because the point is not 'guarded' by the shaft as line tension builds (Largacha *et al.* 2005; Kim *et al.* 2006). The various hook shapes, sizes and degrees of offset affect the overall efficiency of the hook type by influencing the manner in which the point of the hook engages the animal tissue (Yamaguchi 1989; Huse and Fernö 1990).

Figure 1 Various hook types used in pelagic longline gear configurations. Clockwise from left to right, size 5/0 ringed tuna hook, size 7/0 J-style hook, size 9/0 J-style hook, size 16/0 circle hook, size 18/0 circle hook and size 20/0 circle hook. In the present study, we categorized tuna hooks with J-hooks based on the similarities in the orientation of the point relative to the shank (see text for details).

Over the last decade, a relatively small, but growing, number of studies have investigated the biological efficacy of using circle hooks in a variety of fisheries and for a wide diversity of target and bycatch organisms. To date, Cooke and Suski (2004) provide the most comprehensive review of circle hook study results on fishes. Their meta-analysis of 29 studies comparing circle hooks with J-hooks in recreational catch-and-release fisheries revealed a tendency for lower mortality and gut-hooking rates associated with circle hooks, and, in some cases equivalent catch rates. However, Cooke and Suski (2004) also noted several exceptions and identified species-specific factors that may detract from circle hook performance (e.g. differences in mouth morphology). These led to their caveat to fishery managers that circle hooks be promoted only in '…instances for which appropriate scientific data exist'. In the United States and Australia, fishery managers and the conservation community have widely promoted circle hook use for reducing billfish mortality and injury at capture. In other nations and among individual fishers, however, opinions are mixed, especially when such hooks are advocated for high-value pelagic species without prior demonstration of neutral or positive effects. For example, Falterman and Graves (2002) described strong reluctance on the part of Venezuelan pelagic longline fishers targeting yellowfin tuna (*Thunnus albacares*, Scombridae) to merely experiment with circle hooks.

We embarked on the present review to evaluate the empirical information base for the effects of circle hook use with respect to the istiophorid billfishes. Specifically, we compiled reported values of catch, mortality, deep-hooking and bleeding rates along with statistical results that compared circle vs. J-hook performance for these species. Interest in this topic is particularly high given that 2008 marks the first year in which circle hook use in Atlantic waters is mandated for both US commercial longline fishers and, under certain conditions, recreational billfish anglers. In addition to discussing hook performance results with respect to billfish conservation, we briefly touch on circle hook effects on longline target (mostly swordfish and tunas) and other non-target (shark and sea turtle) taxa as these are typically of greater concern to the commercial fisheries than the istiophorids.

Methods

To analyse trends in various hook effects on istiophorid billfishes, we conducted a quantitative review of empirical studies that directly compared the 'performance' of circle hooks vs. J-hooks. Hook performance was measured in terms of catch, mortality, deep-hooking and bleeding rates (see next). Potentially relevant published and grey literature was located via library and electronic database searches, as well as by personal communication with agencies and individuals currently or previously active in this area of research. Once located, candidate papers or reports were required to be documented: (i) species-specific data on one or more istiophorids; and (ii) side-by-side measures of circle vs. J-hook performance. Following Cooke and Suski (2004), if a researcher considered multiple species within a single study, results were not grouped and each set of species-specific results was considered as an independent study.

Expression of catch and mortality rates (i.e. units used) differed among studies according to the fishery examined and/or the methods employed. In recreational fishery studies, catch rates were expressed as a percentage derived from the number of fish brought to the boatside divided by the total number hooked. Catch rates in longline studies were expressed as catch (in numbers) per 1000 hooks deployed. In most studies, mortality rates were expressed as the percentage of living divided by total (dead and alive) fish brought to the boatside. However, in those studies employing electronic tags, mortality rates were inferred by the respective authors from records of vertical swimming behaviour up to 5 days post-release. Deep-hooking and bleeding rates were reported (as percentages) in a consistent fashion across the studies. Researchers generally defined deep-hooking events as those in which the hook was lodged beyond the oesophagus and not visible to the scientific observer when the fish was brought to the side of the vessel. Bleeding rates were calculated as the number of fish noted to be visibly bleeding upon capture divided by the total number brought to the boatside.

For studies comparing multiple circle hook types with J-hooks, only data corresponding to the circle hook size closest (by visual inspection of photographs) to the J-hook were extracted and, if sizes were similar, we focused on the circle hook associated with the highest sample sizes. One study (Prince *et al.* 2007) compared hook performance of a J-hook with that of two types of circle hook along a gradient of 'drop-back' times (i.e. intervals between fish strike and hook engagement). We focused on the performance of only one of their circle hooks (differences among all hook dimensions and sample sizes were minor) because the second 'circle' hook lacked circularity in shape. Furthermore, we focused on comparative hook performance results associated with longest drop-back interval (>15 s) because we deemed these results to be the most representative of the fishery examined. Two Korean pelagic longline studies (Kim *et al.* 2006, 2007) compared circle hook performance with one type and size of tuna hook. In the case of these studies, we followed Largacha *et al.* (2005), Kerstetter *et al.* (2006) and the two Korean studies by categorizing the tuna hooks as J-hooks based mainly on the tuna hook's point-to-shaft orientation, although there was minor curvature of the shaft. In the case of two other studies co-authored by David W. Kerstetter and Joseph E. Serafy, (Kerstetter *et al.* 2006; Prince *et al.* 2007), relevant data on deep-hooking rates were collected, but not reported. In these instances, we accessed the raw data and performed chi-square analyses to test for significant differences between hook types in terms of deep-hooking rate.

Results

We found 11 studies that reported species-specific, side-by-side, circle vs. J-hook performance data for one or more istiophorid billfish (Table 1). Details of the hooks employed are provided in Table 2. Seven of the 11 studies were based on commercial pelagic longline fisheries, with the remainder based on recreational rod-and-reel fisheries. Most studies were based in Atlantic or adjacent waters. Species considered were sailfish (five studies), blue marlin (four studies), white marlin (five studies) and striped marlin (one study). Three studies employed pop-off satellite tags to evaluate the effect of hook type on post-release mortality. Collectively, our review allowed for 30 species-specific, side-by-side comparisons of hook performance. Thirteen of the 30 comparisons revealed statistically significant differences between circle and J-hooks.

Table 1 Chronological list of hook comparison studies for istiophorid billfishes: blue marlin (*Makaira nigricans*), sailfish (*Istiophorus platypterus*), striped marlin (*Tetrapturus audax*) and white marlin (*T. albicans*).

			Catch rate			Mortality rate			Deep-hooking rate			Bleeding rate			
Species	Fishery	Area	Circle	J-hook	Sig.	Circle	J-hook	Sig.	Circle	J-hook	Sig.	Circle	J-hook	Sig.	Reference
Sailfish	LL	CAR				100.0	80.0	nr							Falterman and Graves (2002)
Sailfish	RR	W ATL	78.00	78.0	ns				2.0	46.0	*	6.0	57.0	*	Prince *et al.* (2002a)
Striped marlin	RR	E PAC	63.00	62.0	ns	20.0	29.4	ns	5.0	19.0	*	3.0	21.0	*	Domeier *et al.* (2003)
White marlin	RR	W ATL				0.0	35.0	*	0.0	50.0	*	5.0	45.0	*	Horodysky and Graves (2005)
White marlin	LL	W ATL				7.1	20.0	ns	11.1	22.2	nr				Kerstetter and Graves (2006a)
Sailfish	LL	GOM, CAR				14.3	42.8	ns							Kerstetter and Graves (2006b)
White marlin	LL	W ATL				40.0	33.3	ns							Kerstetter and Graves (2006b)
Blue marlin	LL	W ATL				80.0	25.0	ns							Kerstetter *et al.* (2006)
Sailfish	LL	W ATL	1.42	3.4	ns	33.3	73.1	*	2.2	60.7	*				Kerstetter *et al.* (2006)
White marlin	LL	W ATL	1.20	0.9	ns	53.8	70.0	ns	15.4	50.0	ns				Kerstetter *et al.* (2006)
Blue marlin	LL	C PAC	0.50	0.4	nr										Kim *et al.* (2006)
Blue marlin	LL	C PAC	0.40	0.1	nr										Kim *et al.* (2007)
Blue marlin	LL	GOM	0.29	0.4	ns	53.0	70.0	*							Diaz (2008)
White marlin	LL	GOM	0.60	0.7	ns	47.5	60.0	*							Diaz (2008)
Sailfish	RR	W ATL	69.00	75.0	ns				6.0	57.0	*	5.0	55.0	*	Prince *et al.* (2007)

LL and RR refer to longline and rod-and-reel gear, respectively. Geographic locations (area) of studies are Gulf of Mexico (GOM), Caribbean (CAR), West Atlantic (W ATL), Central Pacific (C PAC) and Eastern Pacific (E PAC). All values are percentages, except for non-whole numbers in the 'catch rate' columns, which are numbers of fish per 1000 hooks. An asterisk, 'ns' or 'nr' in the 'Sig.' (significance) column indicates that hook performance comparisons were either statistically significant, non-significant or not reported, respectively.

Table 2 Details pertaining to the hooks compared in the present analysis. In most cases, when more than one circle or J-hook was used, the original researchers pooled results for single circle hook and J-hook performance values.

Study	Type	Make	Model	Size	Offset
Falterman and Graves (2002)	'J'	Mustad	7698	7/0	nr
	Circle	Mustad	39960	14/0	nr
	Circle	Mustad	39960	16/0	nr
Prince *et al.* (2002a)	'J'	Mustad	9175	6/0	0
	Circle	Eagle Claw	L2004	7/0	5
Domeier *et al.* (2003)	'J'	Eagle Claw	L317MGG	8/0	10
	Circle	Eagle Claw	L2004F	9/0	5
Horodysky and Graves (2005)	'J'	Mustad	9175	7/0	nr
	'J'	Mustad	7731	7/0	nr
	Circle	Mustad	C39952BL	7/0	5
	Circle	Eagle Claw	L2004EL	7/0	0
	Circle	Eagle Claw	L2004EL	9/0	0
Kerstetter and Graves (2006a)	'J'	Mustad	9016	7/0	15
	'J'	Mustad	7698	9/0	15
	Circle	Mustad	39660	16/0	0
	Circle	Mustad	39666	16/0	0
	Circle	LP	nr	18/0	0
Kerstetter *et al.* (2006)	'J'	nr	nr	9/0	10
	'J'	nr	nr	10/0	10
	Circle	nr	nr	18/0	0
Kerstetter and Graves (2006b)	'J'	Mustad	7698	9/0	10
	'J'	Eagle Claw	9016	9/0	10
	Circle	Mustad	39660ST	16/0	0
	Circle	Mustad	39666DT	16/0	0
Kim *et al.* (2006)	'J'	nr	nr	4/0	nr
	Circle	nr	nr	15/0	0
Diaz (2008)	'J'	nr	nr	nr	nr
	Circle	nr	nr	nr	nr
Kim *et al.* (2007)	'J'	nr	nr	4/0	nr
	Circle	nr	nr	15/0	10
Prince *et al.* (2007)	'J'	Mustad	10829BLN	6/0	5
	Circle	Eagle Claw	L2004	8/0	0

LP indicates the manufacturer, Lindgren-Pitman, Inc. (Pompano Beach, FL, USA).
nr, not reported.

Catch rates

Seven studies reported catch rate information allowing for nine species-specific hook performance comparisons (Fig. 2a). Species examined were sailfish, blue marlin, white marlin and striped marlin. Six of the nine comparisons resulted in higher billfish catch rates associated with J-hooks and three indicated higher catch rates associated with circle hooks; no studies found catch differences to be statistically significant. No species-specific patterns in catch rate were evident. Across recreational fishery studies (n = 3 comparisons), billfish catch rates averaged 2.33% higher on J-hooks vs. circle hooks, whereas across longline fishery studies (n = 6 comparisons), mean J-hook catch rate was higher by 0.26 billfish per 1000 hooks.

Mortality

Paired mortality rate data for billfish was reported in seven studies, allowing for 11 comparisons (Fig. 2b). Species examined were sailfish, blue marlin, white marlin and striped marlin. All but two studies were based on longline fisheries. Three studies inferred mortality (i.e. post-release) from data collected with pop-up archival transmitting tags. Of the 11 species-specific hook comparisons, eight indicated higher mortality rates associated with J-hooks and three indicated higher mortality rates with circle hooks.

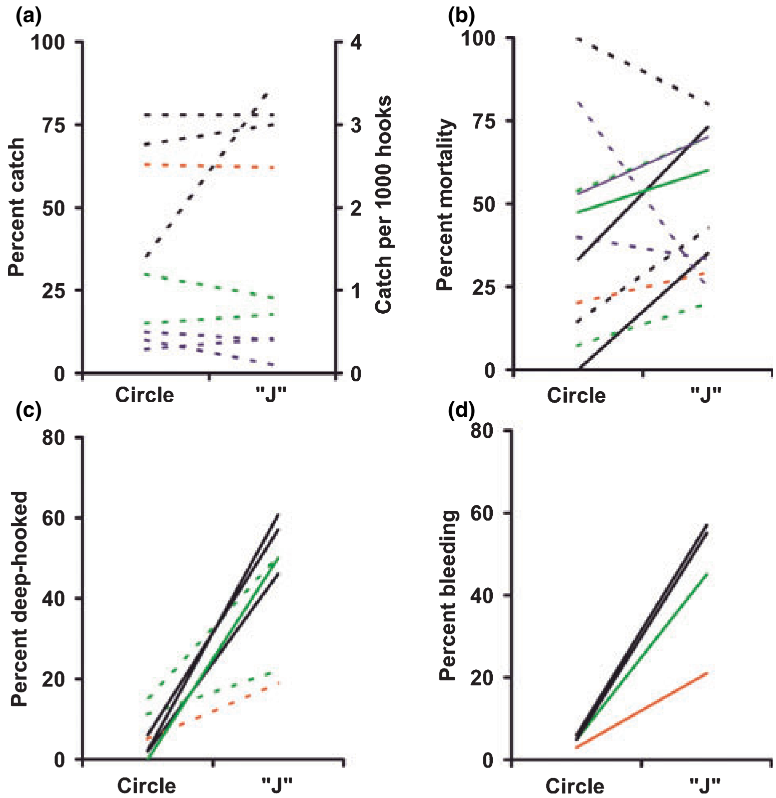

Figure 2 Relative performance of circle and J-hooks with respect to istiophorid billfish catch rate (a), mortality rate (b), deep-hooking rate (c) and bleeding rate (d). Blue, green, red and black lines, respectively, indicate blue marlin, white marlin, striped marlin and sailfish. Solid and dashed lines indicate statistically significant and non-significant results, respectively. Note that the lines are not intended to indicate continuous trends, but rather as a means of drawing attention to significant and non-significant differences among species and hook types.

No species-specific patterns in mortality rate were evident. Four comparisons (three longline and one recreational rod-and-reel fishery study) found mortality rate differences to be statistically significant; all of these indicated higher mortality associated with J-hooks. In the longline fishery studies that examined mortality at boatside ($n = 8$ comparisons), mortality rate averaged 8% higher for billfish captured on J-hooks. Across recreational fishery studies ($n = 2$ comparisons), post-release mortality rates were either equivalent or significantly higher for fish caught with J-hooks; J-hook-associated post-release mortality was also higher in the one longline fishery study that measured this variable, but the difference was not statistically significant.

Deep-hooking

Six studies provided paired deep-hooking rate data on billfishes, which allowed for seven species-specific, hook performance comparisons (Fig. 2c). Species examined were striped marlin, white marlin and sailfish. No species-specific patterns in deep hooking rate were evident. In all seven cases, higher deep-hooking rates were associated with billfish captured on J-hooks; five of these differences (two longline and three recreational rod-and-reel fishery studies) were found to be statistically significant. Across recreational fishery studies ($n = 4$ comparisons), deep-hooking rates averaged 40% higher on J-hooks vs. circle hooks. Similarly, deep-hooking rates for billfish caught on J-hooks in the longline fisheries ($n = 3$ comparisons) averaged 35% higher than on circle hooks.

Bleeding

Four studies reported bleeding rates for billfish captured with circle hooks vs. J-hooks (Fig. 2d); all were recreational rod-and-reel fishery studies. Species examined were sailfish, white marlin and striped marlin. No species-specific patterns in bleeding rate were evident. All four studies reported significantly higher bleeding rates in fish caught on J-hooks as compared with circle hooks. On average, bleeding rate was 40% higher for billfish captured on J-hooks vs. circle hooks.

Discussion

As predicted by Cooke and Suski (2004), the number of circle hook studies has steadily increased over time, which is improving and refining assessments of circle hook effects on different fish species and fisheries. The meta-analysis of Cooke and Suski (2004) and that of Bartholomew and Bohnsack (2005) both considered a single study on a single billfish species (i.e. Prince *et al.* 2002a; sailfish). Since their respective analyses, the body of relevant billfish studies has grown to at least 11 studies, which collectively consider four istiophorid species and allow for 30, side-by-side, hook performance comparisons. Ideally, the quantity of studies relevant to billfishes will continue to expand and their results (and associated details) will be reported in a manner that will allow future assessments to build on the present study. We recommend researchers to strive to separate their results by species, provide detailed hook specifications and images, report as many hook performance metrics (i.e. catch, mortality, deep-hooking and bleeding rates) as their data will enable, and perform statistical tests to allow readers to properly evaluate differences between hook types. For example, our review would have been improved by inclusion of the results of: (i) Mejuto *et al.* (2007) had these researchers not grouped all billfish species; and (ii) Minami *et al.* (2006) had they provided actual values, rather than only a graphic presentation of relative hook performance. We recommend that datasets associated with these and other previous studies be re-visited and their results incorporated in future reviews or meta-analyses.

Partly because most circle hook research examining billfishes has been conducted in the western North Atlantic and/or adjacent waters, most of our knowledge pertains to sailfish, white marlin and, to a lesser extent, blue marlin. Fewer data have been collected on Indo-Pacific sailfish, blue marlin and striped marlin, and none on black marlin. As is the case with virtually all aspects of spearfish ecology and population dynamics, there is virtually no information relevant to circle hook effects on the spearfishes, although some of these species have been reported as captured in a few of the studies considered here. Clearly, appropriate resources should be directed towards further hook performance research and/or data analyses on the less-studied billfish species mentioned before.

Complicating factors in our review were differences in degree of 'offset' of the respective hook types as well as differences in hook sizes. Offset refers to the degree to which the point deviates from the plane of the hook shaft (Prince *et al.* 2007). The expectation is that greater offset increases exposure of the point as the hook moves within the fish when the line tightens, thus increasing the likelihood of deep-hooking and other injuries (Prince *et al.* 2002a). For our billfish analysis, data were considered too limited to separate offset and hook-type effects, although in most cases, non-offset (i.e. 0°) circle hooks were compared with J-hooks with offset values varying from 5° to 15° (Table 2). An exception was the Prince *et al.* (2002a) study on sailfish in which significantly less injuries were associated with a 5° offset circle hook relative to a non-offset J-hook. Prince *et al.* (2002a) suggested circle hooks with offset values <5° were equivalent for sailfish and Cooke and Suski (2004) essentially concurred after examining data on additional species. Watson *et al.* (2005) suggested longline catch rates of target and bycatch species were minor between 0° and 10° offset circle hooks. However, because the Watson *et al.* (2005) circle hook comparisons were indirect, they recommended further research focusing on circle hook offset effects; we strongly agree with this recommendation.

Our analysis is also complicated by differences in hook sizes, though to a lesser degree than offset differences because we focused on those comparisons in which circle and J-hooks had similar dimensions. In their review, Muoneke and Childress (1992) found that hook size effects were mixed on catch and mortality rates of fishes caught recreationally. However, in experimental pelagic longline fishing studies, catch rates tend to decrease with hooks size for both target and bycatch species (Otway and Craig 1993; Erzini *et al.* 1996). The lack of standardization in hook sizes both within and among hook types is a long standing problem, and, as noted by Gilman *et al.* (2006), movement towards an international hook size standard is an issue of high research and management priority. Standards should be based on the dimensions suggested by Otway and Craig (1993) including gape, maximum shank length, maximum width, bill (point) length as well as the more familiar descriptors that include degree of offset and method of construction (e.g. forged, bent-wire, etc.).

Despite considerable interstudy differences (e.g. design, bait and rigging, hook sizes and offset, type of fishery, spatiotemporal, etc.) a broad message can nevertheless be drawn from our review. Most important is that the conservation benefits of circle hook use for billfishes lie first in decreasing injury to billfishes and second in decreasing fish mortality, whether at boatside or post-release. Based on results reported in the literature thus far, substituting J-hooks with circle hooks will have little or no effect on billfish catches: (i) for recreational fishers targeting istiophorids; and (ii) for longline fishers interested in (or ambivalent about) minimizing this form of bycatch. Therefore, given their tendency for reduced mortality and injury, fishery scientists, managers and conservation organizations now have a solid basis for promoting circle hook use in recreational billfish fisheries, provided catch-and-release fishing is practiced. Likewise, circle hook use in pelagic longline fisheries does not appear to significantly reduce billfish interactions, but it does appear to provide more opportunities for fishers to release live billfishes, if they are so inclined, and greater potential for post-release survival. In practice, however, more factors conspire to prevent longline fishers from releasing captured billfishes in good condition (e.g. harsh sea states, higher gunwales, increased time and care required to remove hooks without exacerbating tissue damage and the need to emphasize target species catch and condition over bycatch) as compared with recreational anglers. While participants in the latter fishery are increasingly taking the time to 'resuscitate' exhausted fish (Prince *et al.* 2002b), it may be unrealistic to expect the same level of voluntary care during most pelagic longline fishing operations.

Longline fishery considerations

From the standpoint of billfish conservation, circle hooks appear beneficial (provided billfishes are released alive), however, circle hook adoption in longline fisheries clearly depends how target catches are impacted. Among the longline studies reporting istiophorid results that were reviewed here, circle hook effects on catch rates of target species (i.e. tuna and/or swordfish) were either statistically insignificant (Kim *et al.* 2006, 2007; Diaz 2008) or higher (Falterman and Graves 2002; Kerstetter and Graves 2006b; Kerstetter *et al.* 2006). However, in other longline hook studies, circle hook effects on target species catches appear mixed. For example, Watson *et al.* (2005) found for swordfish that circle hook catch rates were higher or lower than J-hook catch rates depending on bait type. They also found minor catch rate differences for bigeye tuna (*Thunnus obesus*), but significantly less deep-hooking of both swordfish and bigeye tuna with circle hooks, which may lead to higher fish quality at market. Bolten and Bjorndal (2003) reported significantly reduced swordfish catch rates with circle hooks vs. J-hooks. Largacha *et al.* (2005) found negligible target catch rate differences comparing circle and J-hooks in a tuna longline fishery, but significantly lower rates in a fishery targeting mahimahi (*Coryphaena hippurus*).

Circle hook impacts on other longline bycatch species are also important to consider, especially the elasmobranchs and sea turtles, which tend to have life history characteristics that make them extremely vulnerable to depletion. Again, circle hook effects on elasmobranch longline catches vary. For blue shark, three studies report statistically insignificant catch rate differences between circle and J-hooks (Kerstetter and Graves 2006b; Kerstetter *et al.* 2006; Yokota *et al.* 2006), while two report higher catch rates with the former hooks (Bolten and Bjorndal 2003; Watson *et al.* 2005). Only one study reported significantly lower elasmobranch catch rates with circle hooks vs. J-hooks (Kerstetter and Graves 2006b; pelagic stingray, *Pteroplatytrygon violacea*). In contrast, most studies focusing on sea turtle bycatch reduction (Gilman *et al.* 2007; Read 2007) indicate either reduced or equivalent sea turtle catches with circle hooks vs. J-hooks as well as hooking locations that likely cause less damage to the captured individuals (e.g. Bolten and Bjorndal 2003; Largacha *et al.* 2005; Watson *et al.* 2005).

Management implications

Circle hook use (offset ≤10°) was first made mandatory in mid-2004 for US commercial pelagic longline fishers operating in Atlantic waters. Mandatory use of (non-offset) circle hooks by US recreational fishers participating in Atlantic billfish tournaments took effect on the first day of 2008. The present review strongly supports these measures, but their effectiveness is limited to US fishery sectors. For the conservation benefits of circle hook use to be fully realized, international adoption of this terminal gear is necessary. Several international mechanisms may facilitate this technology transfer. For example, the Rio Declaration of 1992 stated in part that 'where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation' (UNCED 1992). Although rarely invoked in discussions of terminal gear types, an application of the precautionary approach (FAO 1995a) in the context of billfishes could include the increased use of circle hooks in both pelagic commercial and recreational fisheries. The technology also appears to meet one of the stated goals in the FAO Code of Conduct for Responsible Fisheries (FAO 1995b): '[T]he use of fishing gear and practices that increase survival rates of escaping fish should be promoted'. As with the performance of circle hooks themselves, some international disagreement exists concerning the interpretation of the precautionary approach to pelagic fisheries management (González-Laxe 2005). Nonetheless, regional fishery management organizations (RFMO) such as ICCAT have set up formal sub-committees to examine the applicability of the approach (see review by Mace and Gabriel 1999), and such RFMO should also investigate the implementation of fishing technologies with scientifically demonstrated ecological benefits.

Conclusions

Our analysis indicates that, for billfish conservation, circle hooks can have clear benefits over J-hooks, particularly in terms of injury reduction. We contend that the evidence is sufficient for promoting circle hooks in both the commercial pelagic longline and the recreational fishing sectors where and when live release is practiced with billfish. While there may be fishing modes where circle hook effects are negative, supporting data have not emerged to date. Until they do, we recommend US managers grant exceptions to circle hook use only when experimental results support such a practice. Our philosophy differs from that of Read (2007). After reviewing recent studies on circle hooks and sea turtle mortality and finding four of five studies had significant conservation benefits, Read (2007) recommended that no fishery be required to adopt circle hooks prior to field testing. From our perspective, the stance of Read (2007) misplaces the 'burden of proof' and is counter to the precautionary approach. Especially in the recreational fishing sector, the diversity of billfish fishing methods and gear is so high that rigorous experimentation of every fishing combination would be overly complex and time-consuming to be practical. Likewise, variation in longline fishery methods and gear is high. Certainly field testing is preferable, but making highly specific experiments a precondition for a given fishery change could potentially delay benefits for species known to be severely overfished, threatened or endangered.

As noted by Cooke and Suski (2004), circle hooks are not a panacea for over-exploited fish stocks – for billfish, their use appears to have little or no effects on catch rates. Given that the multinational longline fisheries represent a major component of the mortality of billfishes of the world and because substantial reduction in longline fishing effort seems unlikely in the near future, additional terminal gear research is warranted. Specifically, there is a pressing need for baits or treatments (e.g. repellents, electric and magnetic fields, light, sound, etc.) that are accepted by target species, yet avoided to some degree by bycatch species, including the billfishes. Even a modicum of success in this front, if applied in combination with other measures (e.g. time-area closures, circle hook use), could improve the outlook for pelagic fish stocks and the fisheries with which they interact.

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