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Review

Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments

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ABSTRACT

Circle hooks have been proposed as a means of reducing the by-catch mortality of sea turtles in pelagic longline fisheries to sustainable levels. I examine the efficacy of circle hooks as a sea turtle conservation measure by examining the results of field trials conducted in the western North Atlantic, the Azores, the Gulf of Mexico, and Ecuador. These experiments employed more than a million and a half hooks between 2000 and 2004 and, in general, were well designed, conducted and analyzed. Four of five experiments demonstrated a significant reduction in capture rate and/or hooking location, indicating that circle hooks would reduce overall mortality. In one trial, however, circle hooks reduced catches of target species to such a degree that their use was impractical. I conclude, therefore, that circle hooks have the potential to reduce the mortality of sea turtles captured in many (but not all) pelagic longline fisheries, but that they should be field tested in a rigorous experiment before they are required in any fishery. Circle hooks will not reduce mortality rates of sea turtles in every pelagic longline fishery; each case needs to be tested before this measure is adopted. Circle hooks reduce turtle mortality because of their shape and size and the ways that these parameters interact with the size of turtles interacting with the fishery. Circle hooks may cause a reduction in turtle mortality by decreasing the incidence of hook ingestion as well as reducing capture rate, particularly for loggerhead sea turtles.

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1. Introduction

By-catch, the unintended, capture, mortality and discard of non-target species, is a significant issue in current fishery management (Harrington et al., 2005). To date, most attention has focused on by-catch of commercially valuable species, but many other organisms are killed accidentally in the world's fisheries. Of particular concern are long-lived species, such as seabirds, marine mammals, elasmobranchs, and sea turtles, which cannot withstand high levels of mortality due to their life histories (Heppell et al., 2005).

Sea turtles and seabirds are taken in many fisheries, but considerable attention has been focused recently on their by-catch in pelagic longline fisheries (Lewison et al., 2004). Longlines are used to target many pelagic fish species throughout the world's oceans and are responsible for most of the world's swordfish (*Xiphius gladius*) catch and a large proportion of global tuna (*Thunnus*) catches (Lewison et al., 2004). By-catch in pelagic longline fisheries is responsible, at least in part, for the dire conservation status of a number of sea turtles and seabirds (Spotila et al., 2000; Tuck et al., 2003). Complicating assessment of these by-catches is the vast scale over which longline fisheries are prosecuted and the highly migratory nature of many species taken as by-catch (e.g. Weimerskirch and Wilson, 2000; Ferraroli et al., 2004).

The sea turtles taken most frequently in pelagic longlines are loggerheads (*Caretta caretta*) and leatherbacks (*Dermochelys coriacea*). Lewison et al. (2004) estimated that more than 200,000 loggerheads and 50,000 leatherbacks were taken as by-catch in pelagic longline fisheries in 2000. Loggerheads are captured on longlines as a result of hooking, either in the mouth or elsewhere on the body as they attempt to ingest baited hooks. In contrast, leatherbacks are typically entangled in the mainline or gangions, but are also occasionally hooked. Most turtles captured on longlines are alive when the gear is retrieved, particularly in shallow-set fisheries, so the fate of captured animals after release is a critical factor in determining their mortality. The mortality rate of sea turtles captured in pelagic longlines is, therefore, a product of capture rate and the mortality rate of released turtles. The location of a hook in the body of a turtle greatly influences its subsequent probability of survival. Fully ingested hooks are most likely to cause mortality (Epperly and Boggs, 2004).

A variety of measures have been developed to reduce the by-catch mortality of sea turtles and seabirds in pelagic longline fisheries (Gilman et al., 2005, 2006). Techniques to address sea turtle by-catch include; time-area closures; voluntary measures (e.g. moving after a by-catch); de-hooking procedures to increase post-release survival; and circle hooks, intended to reduce both capture rate and post-release mortality (Lokkeborg, 2004; Gilman et al., 2006). The barbs of circle hooks are pointed back towards the shaft of the hook and the hooks are often wider than the J hooks or Japanese tuna hooks typically employed (Fig. 1). Circle hooks are currently being tested in many fisheries (see Table 2 in Gilman et al., 2006) and have been proposed by fisheries managers as a practical and economical measure to reduce sea turtle mortality in pelagic longline fisheries (e.g. NMFS, 2005). The use of circle hooks as a conservation measure is yet unproven, however, and to date there has been no comprehensive review of their promise as a means of reducing sea turtle mortality.

The purpose of the present paper, therefore, is to assess the efficacy of circle hooks in reducing the mortality of sea turtles in pelagic longline fisheries. In addition, I examine the effects of circle hooks on the catch of target species and, wherever

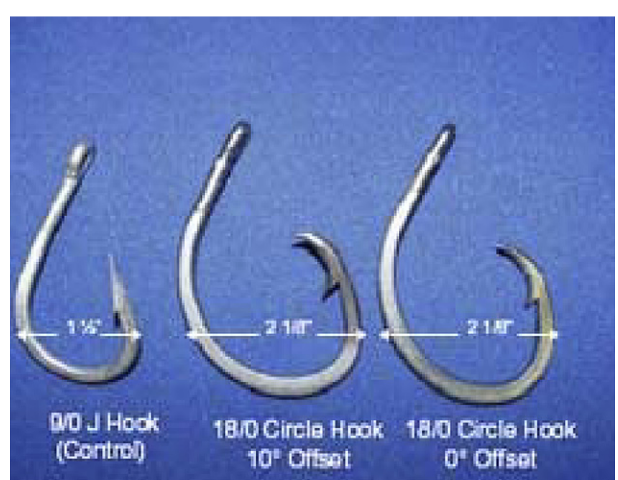

Fig. 1 – Examples of circle and J-hooks used in experiments designed to reduce sea turtle mortality in pelagic longline fisheries. Photo courtesy of NOAA Fisheries.

possible, on other non-target species taken as by-catch. I review field trials conducted in the western North Atlantic, the Azores, the Gulf of Mexico, and Ecuador. These are the only trials for which sufficient information was available to allow a detailed review. Only one of these experiments has been completely analyzed and published, however, and results from the other trials should be considered preliminary.

2. Experiments in the Western North Atlantic

Loggerhead and leatherback sea turtles are taken as by-catch in the US pelagic longline fishery in the North Atlantic. Between 1992 and 1999 more than 7500 loggerheads and 6000 leatherbacks were taken as by-catch in this fishery, although most of these turtles were released alive (Yeung, 2001). A large proportion of these by-catches (75% of loggerheads and 40% of leatherbacks) occurred during the summer near the Grand Banks, southeast of Newfoundland in an area known as the Northeast Distant (NED) Statistical Sampling Area. The primary target species of the longline fishery in this area is swordfish, although bigeye tuna (*Thunnus obesus*) is also retained.

In the North Atlantic, loggerhead turtles are classified as *threatened* and leatherback sea turtles are considered *endangered* under the US Endangered Species Act. As a result, the US National Marine Fisheries Service (NMFS) must consider whether any federal action, such as authorizing a fishery, will jeopardize the continued existence of these species. In a Biological Opinion completed in June 2000, NMFS concluded that by-catches in the pelagic longline fishery jeopardized the continued existence of loggerhead and leatherback turtles in the North Atlantic (NMFS, 2000). As a result of this finding, NMFS implemented emergency regulations to close a large portion of the NED area to pelagic longline fishing in October 2000 (NMFS, 2000). Following the completion of a second Biological Opinion in June 2001, the closure was extended through the entire 2002 and 2003 fishing seasons (NMFS, 2001a,b). NMFS estimated that a 55% reduction in by-catch mortality was necessary to allow for the recovery of these two species (NMFS, 2001a).

As it extended the closure into the 2001 season, NMFS announced a research program, to be conducted in co-operation with the pelagic longline fleet, which would develop and evaluate new methods to reduce the number of interactions between longlines and sea turtles (NMFS, 2001a). This program allowed vessels to participate in an experimental fishery in the NED area, providing they met a series of requirements. The vessels were also compensated financially for participating in the experiment. The research program was designed to achieve a target mortality reduction of 55%, either through reducing the number of turtles captured or by improving their post-release survival (NMFS, 2001a). The experimental fishery was designed to last for three years (2001, 2002 and 2003 fishing seasons) and intended to evaluate measures that could be exported to international longline fleets (NMFS, 2001a).

NMFS conducted a series of workshops to evaluate potential measures that could be tested in the NED experimental fishery. These measures included: variations in hook type; changing or dyeing bait; testing de-hooking gear; and modifying the depth and temperature at which gear was set (NMFS, 2001c). In April 2001, NMFS hosted a meeting to plan experiments to be conducted in the NED area, and to ensure co-ordination between these research activities and those conducted elsewhere, particularly in the Azores and the Pacific (Watson et al., 2002). These workshops resulted in submission of a permit to conduct the experimental fishery in June 2001 (NMFS, 2001a).

The prioritized list of mitigation measures to be tested in 2001 were: (1) evaluation of blue-dyed squid bait; (2) evaluation of mackerel bait; (3) moving hooks away from floats (decreasing depth of set); (4) use of stiff buoys and gangions; and (5) offset circle hooks (Watson et al., 2002). Due to logistical constraints, the 2001 NED experiment evaluated only the first and third priorities and circle hooks were not tested. In 2002 and 2003, however, circle hooks were evaluated, together with a variety of other measures. I review the results of these two years of experimentation below.

2.1. Experimental design

In both 2002 and 2003 the NED experiments focused on hook style and bait type. Two bait species were evaluated: squid (*Illex* spp.) and mackerel (*Scomber scombrus*). In general, experimental treatments of bait and hook type were compared against a control that consisted of a standard 9/0 J-hook with a 20–25° offset, baited with squid (JS); this was the typical configuration of hook and bait used in the NED fishery (Garrison, 2003).

For consistency, I have adopted the shorthand designations for experimental treatments used by Watson et al. (2005). In 2002 the following treatments were evaluated (Watson et al., 2003a):

(1) Non-offset 18/0 circle hook with squid (C_1S).
(2) 10° offset 18/0 circle hook with squid (C_2S).
(3) 10° offset 18/0 circle hook with mackerel (C_2M).
(4) 20°–25° 9/0 J hook with mackerel (JM).

There was no evaluation of non-offset circle hooks baited with mackerel (C_1M) due to the difficulty of placing this bait on non-offset hooks (Watson et al., 2005).

In 2003 evaluation of two treatments continued and a third was added. A fourth treatment (Non-offset 10/0 Japanese tuna J hook) was terminated to increase sample size for the other treatments (Watson et al., 2004a). This treatment was also being evaluated concurrently by the research group working in the Azores (see below). Thus, in 2003 the following treatments were evaluated:

(1) Non-offset 18/0 circle hook with squid (C_1S) – continued from 2002.
(2) 10° offset 18/0 circle hook with mackerel (C_2M) – continued from 2002.
(3) 10° offset 20/0 circle hook with mackerel (C_3M) – new in 2003.

Control and experimental hooks were alternated in each longline section (although see below). Several set configurations were used to evaluate the effects of the experimental treatments. For example, in 2002, three configurations were used:

(A) C_1S versus JS.
(B) C_2S versus JS.
(C) C_2M versus JM.

Vessels rotated among the three configurations during the fishing season (Watson et al., 2005).

The alternation of control and experimental hooks along each longline section was used to minimize the potential for confounding effects specific to a set (e.g. location, water temperature, turtle density, or other factors). Unfortunately, this protocol was not followed for treatments that used mackerel bait, because only one bait type (squid or mackerel) was used in a single set. Therefore, comparisons between treatments that employed mackerel as bait (3, 4 and 5 above) and the control (JS) are somewhat difficult to interpret (see below). Squid and mackerel were not alternated on hooks within a set to avoid possible interaction effects (Watson et al., 2005).

Some characteristics of fishing gear and practices (e.g. hook placement, setting time, use of light sticks, bait size and hook manufacturer) were standardized among participating vessels; other aspects of the gear (e.g. length of mainline and leader lines) were allowed to vary among vessels, but were consistent within a trip (Watson et al., 2005). Each vessel participating in the experiment carried an observer who collected data on catches of target and non-target species.

2.2. *Analysis*

Generalized linear models were used to evaluate the by-catch rate of turtles (numbers per thousand hooks) and catch rate of target species (kg of swordfish and tuna per thousand hooks). Logistic regression models were used to evaluate the effects of various factors, including hook and bait type, on the by-catch rates of turtles, with separate analyses conducted for loggerheads and leatherbacks. This approach was used to deal with binary data (i.e. catch or no catch of a turtle on each hook). Traditional regression analysis was used to evaluate the effects of these factors on the catch rates of target species (swordfish and bigeye tuna). Catch probability ratios for different hook types were expressed as odds ratios derived from the fitted regression models. Sets were used as experimental units. Details of the analytical techniques used are presented in Shah et al. (2004).

A power analysis was conducted prior to the experiment to determine the number of hooks required to detect a 25% and 50% reduction in the by-catch rate of loggerhead and leatherback sea turtles (see Appendix A in Watson et al., 2005). Observer data from the Grand Banks fishery in 1991–1999 (Yeung, 2001) were used to derive expected by-catch rates. The number of hooks fished in 2002 alone (more than 400,000) provided an 80% probability of detecting a 25% reduction in the by-catch rate of loggerheads and a 50% reduction in the by-catch rate of leatherbacks (Watson et al., 2005).

In general, the analytical techniques used were appropriate for the data set generated during these experiments. In an ideal world, each experimental treatment would have been contrasted against the control (JS) in every set. In other words, each set should have alternated control and treatment hooks. This was done for all sets using squid baits, but, as described above, treatments with mackerel were not contrasted directly with control hooks in the same set. Thus, it is possible that confounding factors could have influenced the comparisons of treatments using mackerel bait (3, 4 and 5 above) and the control. However, there were no significant differences in the mean water temperatures in sets using mackerel and squid and the spatial and temporal distribution of the two set types were generally similar (Figs. 3 and 4 in Watson et al., 2005).

2.3. *Results*

The results of these experiments are presented, in various formats, in Watson et al. (2003a, 2004a, 2005), NMFS (2004), Shah et al. (2004) and summarized in Table 1. In a few cases there are slight discrepancies in the results presented in these reports; wherever this occurred I used summaries from the most recent version.

In both 2002 and 2003, the use of circle hooks resulted in a significant reduction in the by-catch rate of both loggerhead and leatherback sea turtles (Table 2). Interestingly, the use

Table 1 – Summary of experiments designed to assess the efficacy of circle hooks in reducing the mortality of sea turtles

Location	Year	Vessels	Sets	Hooks	LH	LB	Other
NED	2002	13	489	427,382	96	148	0
	2003	11	539	578,050	92	79	1
Azores	2000	1	93	138,121	232	4	1
	2001	1	60	88,150	44	1	0
	2002	1	48	75,511	18	3	0
	2003	1	73	114,417	143	5	0
Gulf of Mexico	2004	3	61	29,570	0	3	0
Ecuador (Tuna)	2004	136	185	20,570	0	0	16
Ecuador (Mahi)	2004	7	126	32,200	0	0	58

Data from the NED were taken from Watson et al. (2003a, 2004a, 2005). Data from the Azores were taken from Bolten et al. (2002) and Bolten and Bjorndal (2003, 2004, 2005). Data from Ecuador were taken from Largarcha et al. (2005). LH, LB and other refer to numbers of captured loggerhead, leatherback and other species of turtles, respectively.

Table 2 – Reduction in capture rate (turtles per thousand hooks) of sea turtles in the NED experimental fishery

Treatment	Loggerheads			Leatherbacks		
	2002	2003	Both	2002	2003	Both
Non-offset 18/0 circle hook with squid	0.88	0.65	0.74	0.64	0.90	0.75
10° offset 18/0 circle hook with squid	0.85			0.50		
Combined 18/0 circle hook with squid	0.86			0.57		
10° offset 18/0 circle hook with mackerel	0.90	0.86	0.88	0.65	0.56	0.63
9/0 J hook with mackerel	0.71			0.66		
10° offset 20/0 circle hook with mackerel		0.91			0.72	

All comparisons are made against 9/0 J hooks baited with squid. Data were taken from Watson et al. (2003a, 2004a, 2005) and Shah et al. (2004). *Both* refers to the years 2002 and 2003 combined.

of mackerel bait with standard 9/0 J-hooks also significantly reduced the by-catch of both turtle species in 2002; in fact, this was the greatest reduction observed in the by-catch rate of leatherback turtles during that year (Table 2).

In 2002, circle hooks used with mackerel bait (treatment C_2M) reduced loggerhead by-catch rate by 90%; slightly lower reductions were achieved by using offset or non-offset circle hooks with squid (Table 2). When the C_1S and C_2S treatments were combined (i.e. all circle hooks with squid), loggerhead by-catch rate in 2002 was reduced by 86% (Watson et al., 2005). Circle hooks baited with both squid and mackerel also resulted in a significant reduction of loggerhead by-catch rate in 2003 (Table 2). Of the two treatments repeated in 2003, there was a significant effect of year in the C_1S treatment (a lower reduction in by-catch rate observed in 2003), but not in the C_2M treatment (Shah et al., 2004). Importantly, the use of circle hooks also resulted in a significant change in hooking location. For example, in 2002, most (69%) loggerheads caught on J-hooks had swallowed the hooks, compared to only 27% of those taken on circle hooks (Watson et al., 2005); these results were confirmed in 2003 (Watson et al., 2004a).

The reduction in leatherback turtle by-catch rate observed from the use of circle hooks in 2002 was significant, but more modest than that documented for loggerheads (Table 2). When both C_1S and C_2S treatments were combined, the by-catch rate of leatherbacks was reduced by 57% compared with the standard J-hooks and squid in 2002 (Watson et al., 2005). Slightly better results were observed with circle hooks baited with mackerel (C_2M). There were significant effects of year in both treatments repeated in 2003 (a considerably greater reduction for C_1S and a decreased reduction in C_2M) (Shah et al., 2004). Watson et al. (2005) note that the effect of circle hooks on hooking location was not as pronounced for leatherbacks as for loggerheads, although significantly fewer turtles were hooked externally with circle hooks than J-hooks in 2002.

As noted above, all turtles captured in the 2002 and 2003 NED experimental fishery were released alive. To determine the ultimate efficacy of circle hooks (and other mitigation measures), therefore, it is necessary to examine not only changes in by-catch rates of turtles, but also to evaluate their survival after release. A study of post-hooking mortality is underway in the Atlantic (Watson et al., 2005), although assessment of post-hooking survival is complex and controversial (e.g. Chaloupka et al., 2004a; Hays et al., 2004; Chaloupka et al., 2004b).

Epperly and Boggs (2004) used a set of criteria established by a group of experts to evaluate the probability of mortality for turtles released in the NED experimental fisheries in 2002 and 2003. Six categories of mortality categories were established based on the location of the hook on the turtle. These categories were then applied to standards determined by NMFS that further stratified the likelihood of mortality based on whether or not the hook was removed and, if not, how much line was removed. In total, sixteen categories of entanglement were examined for both loggerhead and leatherback sea turtles. This analysis combined all circle hooks, regardless of offset or bait type, due to the “weak evidence” for an effect of these factors and the relatively small sample sizes involved (Epperly and Boggs, 2004).

A qualitative analysis of these results suggests that circle hooks reduced the post-hooking mortality of loggerheads. The estimated mortality ratio (the proportion of hooked turtles likely to die after release) of loggerheads captured with J-hooks in the NED experimental fishery was 0.33; the mortality ratio for loggerheads captured with circle hooks was reduced by half (0.17). This difference is due to the fact that most loggerheads captured on J-hooks swallowed the hook, but relatively few turtles ingested circle hooks. These results are consistent with experiments designed to evaluate the effect of hook size and shape on the probability of ingestion conducted with captive turtles (Watson et al., 2003b). In these experiments, turtles of the size encountered by the pelagic longline fishery in the NED seldom ingested 18/0 circle hooks due to the width of the hook, as opposed to narrower hooks (such as the 9/0 J-hook) that were frequently ingested.

In contrast to the results for loggerheads, there was little difference in the mortality ratio between circle and J-hooks for leatherback turtles. The estimated post-hooking mortality ratio for J-hooks was 0.14, compared to 0.13 for circle hooks (Epperly and Boggs, 2004). As noted by Watson et al. (2005), leatherbacks are less prone to ingest baited hooks and more likely to become “foul-hooked” than loggerheads, so the effect of circle hooks is likely to be less pronounced with this species.

Both hook and bait type significantly affected the catch rates of target species in the NED experimental fishery (Table 3). In general, the use of circle hooks with squid bait decreased the catch per unit effort (CPUE) of swordfish by

Table 3 – Change in swordfish and bigeye tuna catch per unit effort (kg retained per 1000 hooks) in the NED experimental fishery

Treatment	Swordfish			Bigeye tuna		
	2002	2003	Both	2002	2003	Both
Non-offset 18/0 circle hook with squid	−0.33	−0.29	−30.00	0.29	0.20	0.24
10° offset 18/0 circle hook with squid	−0.29			0.22		
Combined 18/0 circle hook with squid	n/a			0.26		
10° offset 18/0 circle hook with mackerel	0.30	0.09	0.19	−0.81	−0.88	−0.80
9/0 J-hook with mackerel	0.63			−0.90		
10° offset 20/0 circle hook with mackerel		0.08			−0.90	

All comparisons are made against 9/0 J hooks baited with squid. Data were taken from Watson et al. (2003a, 2004a, 2005) and Shah et al. (2004). The term *both* refers to the years 2002 and 2003 combined. Note that circle hook treatments with squid bait in 2002 could not be combined due to a significant difference between the two treatments.

approximately 30% and increased the CPUE of tuna by about 24%. The use of mackerel with standard J-hooks increased the catch rates of swordfish by 63% and decreased the catch rates of tuna by 90%. When mackerel was used with circle hooks, catch rates of swordfish increased slightly, but tuna catch rates dropped precipitously (Table 3). There were significant year effects in three of the four treatments repeated in 2002 and 2003 (Shah et al., 2004).

A number of fishes, marine mammals and seabirds were also taken as by-catch in the 2002 and 2003 NED experimental fishery (Watson et al., 2003a, 2004a, 2005). For most of these species, too few individuals were taken to evaluate the effects of hook type or bait species on by-catch rates, although Watson et al. (2005) present a summary of by-catch rates of blue sharks (*Prionace glauca*) in the 2002 experimental fishery (Table 4). Blue sharks were the most common species captured in 2002 and all but a few were discarded. In fact, blue sharks were captured more frequently than swordfish by an order of magnitude (Watson et al., 2005). The use of circle hooks baited with squid resulted in a significant, but small, increase in blue shark CPUE. Conversely, the use of mackerel bait, either with circle or J-hooks, resulted in a significant and reasonably large reduction in blue shark CPUE (Table 4).

2.4. General conclusions

The 2002 and 2003 experiments conducted by Watson et al. (2005) in the NED area were well designed, carefully executed and analyzed in an appropriate manner. The work has been peer reviewed and published in the primary scientific literature. In addition, an early version of this work was subjected to additional external peer review by the Center of Independent Experts.

Table 4 – Change in blue shark catch per unit effort (kg per 1000 hooks) in the NED experimental fishery

Treatment	2002
Non-offset 18/0 circle hook with squid	0.08
10° offset 18/0 circle hook with squid	0.09
Combined 18/0 circle hook with squid	n/a
10° offset 18/0 circle hook with mackerel	−0.31
9/0 J-hook with mackerel	−0.40

All comparisons are made against 9/0 J hooks baited with squid. Data were taken from Watson et al. (2005). Note that circle hook treatments with squid bait could not be combined due to a significant difference between the two treatments.

In many respects, these experiments serve as models of how such research should be conducted. Consideration was given to the commercial viability of potential mitigation measures (Gilman et al., 2006) and the experiments were conceived, designed and conducted with the direct involvement of commercial fishermen. A power analysis was conducted prior to the experiment to determine the number of observations required to meet the necessary reduction in by-catch rates and the number of mitigation measures tested each year was relatively small, allowing sufficient power to evaluate their effectiveness. By-catch rates in control gear were sufficiently high (e.g. 0.399 loggerheads/1000 hooks and 0.258 leatherbacks/1000 hooks in 2003; Watson et al., 2004a) to assess the efficacy of mitigation measures. And, finally, the experimental design attempted to minimize the effects of other sources of variation that could affect the results, although this was not possible in all cases (e.g. the use of mackerel and squid baits in different sets, as described above).

In addition to the research on the effect of hook and bait type on by-catch rate, these experiments allowed for the development and testing of equipment and methods to improve the handling and safe release of turtles captured in longline fisheries (Epperly et al., 2004).

From the two years of experimentation in the NED area, we can conclude:

1. The use of circle hooks led to a significant reduction in capture rate and a significant change in the location of hooking for loggerheads.
2. The use of circle hooks led to a smaller but still significant reduction in the by-catch rate, but did not change the location of hooking, for leatherbacks.
3. Much of the observed reduction in by-catch rates held across years, when particular hook and bait types were tested in both 2002 and 2003, although there was significant inter-annual variation in the results of some tests.
4. Within the relatively narrow ranges tested, the size (18/0 or 20/0) or degree of offset (0–10°) of the circle hooks used did not greatly affect the by-catch rate. From work with captive turtles, however, it appears that the width of a

hook is an important determinant of whether or not a hook is ingested, at least when a broader range of hook sizes (e.g. 16/0–20/0) are considered (Watson et al., 2003b).

5. The use of mackerel bait with J-hooks also resulted in a significant reduction in by-catch rates of both species of turtles. The degree of reduction was less for loggerheads than the use of circle hooks (with either squid or mackerel bait), but comparable to the reduction in by-catch rate observed for leatherbacks when circle hooks were used.
6. The use of circle hooks and squid bait resulted in a significant reduction in the CPUE of swordfish and a significant increase in the CPUE of bigeye tuna, the secondary target species of the fishery. The use of circle hooks with mackerel resulted in a significant, but relatively modest increase in swordfish CPUE and a large decrease in tuna CPUE. In general, the use of mackerel as bait had a dramatic and negative impact on tuna CPUE.
7. It is not possible to assess the effect of circle hooks on the by-catch rate or post-hooking mortality of other species taken as by-catch in the NED experimental fishery, due to the small numbers of individuals taken. An assessment of the effects of circle hooks could be made only for blue sharks. The use of circle hooks baited with squid resulted in a significant, but small, increase in blue shark CPUE. Conversely, the use of mackerel bait, either with circle or J-hooks, resulted in a significant and reasonably large reduction in blue shark CPUE.

3. Experiments in the Azores

In September 1998 a workshop was held to design an experiment to test potential gear modifications that would reduce the rate of capture and subsequent mortality of sea turtles in the Azores longline fishery (Bolten et al., 2000). A small pilot observer program in the Azores had revealed high by-catch rates of loggerhead and leatherback turtles (0.753 turtles per thousand hooks in July 1998), suggesting that experimentation was feasible (Prieto et al., 2000).

The Azores longline fishery is similar to the western North Atlantic fishery in some, but not all, respects (da Silva, 2000). The gear is set at dusk and hauled at dawn and uses squid and mackerel (*Scomber japonicus*) as bait. Unlike the US fleet, Azorean fishermen seldom use light sticks. Loggerheads are taken most frequently as by-catch, although leatherbacks are also captured; almost all turtles are released alive (Ferreira, 2005).

Participants in the 1998 workshop devised an experimental design to examine the effect of three factors on turtle capture rate: hook type; bait type and depth of setting (Bolten et al., 2000). A power analysis (Wetherall, 2000) used data from the pilot observer program to determine the likelihood of detecting effects of these factors given the anticipated sample size, which was fixed by logistical constraints. This analysis revealed that a sample of approximately 80 sets was unlikely to provide sufficient statistical power to detect an effect of two factors (hook size and bait type). The experimental design was subsequently modified to examine only a single factor, hook type, and field trials commenced in 2000.

3.1. *Experimental design*

In 2000 the Azores experiment examined the effect of hook type on the catch rate and hooking location of turtles (Bolten et al., 2002). Three treatments were examined:

(1) Non-offset 9/0 J hooks.
(2) Offset 9/0 J hooks.
(3) Non-offset 16/0 circle hooks.

The hooks were alternated on gangions along the mainline. There were eight hooks between buoys, so that the position of each hook type varied along the mainline in each set. Squid was the only bait used. A single commercial longline vessel was chartered by NMFS to conduct the experiment between July and December.

In 2001 the experiment continued with the same longline vessel (Bolten and Bjorndal, 2003). The experimental protocol was identical to that employed in 2000, with the substitution of a single hook type:

(1) Non-offset 9/0 J hooks.
(2) Non-offset 18/0 circle hooks.
(3) Non-offset 16/0 circle hooks.

In the third year of the experiment (2002), the protocol was repeated with a different vessel and the following treatments (Bolten and Bjorndal, 2004):

(1) Offset 18/0 circle hooks.
(2) Offset 16/0 circle hooks.
(3) Non-offset 16/0 circle hooks.

Finally, in 2003 the same vessel was chartered to fish the following hook types:

(1) Non-offset 18/0 circle hooks.
(2) Non-offset 16/0 circle hooks.
(3) Japanese Tuna hooks (3.6 mm S/S).

The non-offset 18/0 circle hooks used in 2003 were obtained from a different manufacturer than those used in 2001. The use of the Japanese tuna hook was discontinued after 27 sets due to a high catch rate of loggerheads, many of which were hooked in the throat (Bolten and Bjorndal, 2005).

Thus, only a single hook type (Non-offset 16/0 circle hook) was tested in all four years of the experiment. The experiment did not evaluate the predominant hook type used in the Azores longline fishery, the Ancora 17/0 J-hooks (da Silva, 2000). It is unfortunate that a single *control* treatment (e.g. the Ancora hook) was not used in all years of the study, particularly given the significant inter-annual variation observed in loggerhead turtle CPUE (see below).

The strength of this approach was the alternation of the three hook types along the mainline and the use of a single bait type. In addition, the use of a chartered vessel each year minimized the introduction of potentially confounding factors within a year, such length of mainline, length of leader lines, etc. One potentially important confounding factor was a shift in 2001 to target blue sharks, due to an increased market demand. This practice continued in 2002 and 2003 (Bolten and Bjorndal, 2005).

3.2. *Analysis*

To date, a full description of the experimentation in the Azores has not been published in the peer-reviewed literature. The results are available only as summary reports, in which only preliminary analyses have been conducted.

Exact binomial and chi-square tests were used to examine differences in the number of loggerhead turtles captured on each hook (Bolten and Bjorndal, 2005). The treatments varied each year, so it is not possible to examine the effect of hook types across years. Chi-square tests were used to assess hooking location in loggerhead turtles.

To date, little analysis of the effect of hook type on swordfish catch has been presented, although a preliminary report used Chi-square tests to evaluate the number of swordfish taken on each hook type (NMFS, 2001). The number of blue sharks captured was assessed using Friedman rank sum tests (Bolten and Bjorndal, 2005). No results have been presented on the effect of hook type on catches of other target species.

3.3. *Results*

Results of these experiments are presented in Bolten et al. (2002); Bolten and Bjorndal (2003, 2004, 2005) and are summarized in Table 1. Some CPUE values for loggerheads were inconsistent among reports; in such cases, I present the most recent summaries.

There were no significant differences in the number of loggerhead turtles caught on the three hook treatments used in 2000, 2001 or 2002. In contrast to the results of the NED experiment, circle hooks did not reduce the capture rate of turtles when compared with J-hooks in either 2000 or 2001 (Table 5). In fact, the use of circle hooks did not lead to any obvious trend towards lower capture rates The only significant reduction in capture rate was observed in 2003, when Japanese tuna hooks took significantly more turtles than both types of circle hooks in the first 27 sets, after which use of this hook type was discontinued. The 18/0 circle hooks also captured significantly fewer turtles than the 16/0 circle hooks in 2003 (Bolten and Bjorndal, 2005). In general, there was a tendency for larger, offset hooks to capture fewer turtles, although these results were significant only in 2003 (Table 5). Interpretation of these contrasts is hampered by relatively a small sample of sets and significant inter-annual variation in CPUE of loggerheads; the CPUE on 16/0 circle hooks in 2000 was almost six times that in 2002, for example.

When the four years of experimental results were combined and circle hooks were compared to J-hooks (Bolten and Bjorndal, 2005), there was a significant difference in the location in which loggerheads were hooked. Most (60%) of the loggerheads that ingested J-hooks were hooked in the throat, compared with only 13% of those that had ingested circle hooks. In addition, turtles were significantly more likely to be hooked in the throat with Japanese tuna hooks than either circle hook used in 2003. These findings suggest that the use of circle hooks will lead to a reduction in post-hooking mortality (Bolten and Bjorndal, 2005). Over the course of the experiment, 13 leatherback turtles were captured; most were entangled in lines.

As noted above, only a cursory analysis of the effect of hook type on target species CPUE is presented in the reports. A preliminary report (NMFS, 2001c) indicated that the use of circle hooks in 2000 resulted in a 31% reduction of swordfish catch by number and that this result was statistically significant. It is not clear which contrast this refers to, although examination of the CPUE data (Table 6) suggests that it may have been between 9/0 non-offset J hooks and 16/0 non-offset circle hooks.

As noted by Bolten and Bjorndal (2004), interpretation of the blue shark data is complicated by the fact that the fishery began to target these sharks in 2001. Examining the only treatment used in all four years (16/0 non-offset circle hooks), it is clear that blue shark CPUE increased when the species was targeted, as expected (Table 7). It is not possible to assess the effect of circle hooks on the by-catch of other species, as none are mentioned in the reports.

3.4. *General conclusions*

Like the experiments of Watson et al. (2005), the work in the Azores was carefully designed and executed. In some re-

Table 5 – Capture rate (turtles per thousand hooks) of loggerhead turtles in the Azores pelagic longline experiments

Treatment	2000	2001	2002	2003(a)	2003(b)
9/0 non-offset J	1.82	0.48			
9/0 offset J	1.37				
16/0 non-offset circle	1.85	0.71	0.32	1.91	0.63
18/0 non-offset circle		0.31		1.18	0.41
16/0 offset circle			0.24		
18/0 offset circle			0.16		
Japanese tuna hook				4.55	

Data were taken from Bolten et al. (2002) and Bolten and Bjorndal (2003, 2004, 2005). The experimental protocol varied in 2003; see text for detail.

Table 6 – Capture rate (catch per thousand hooks) of swordfish in the Azores pelagic longline experiments

Treatment	2000	2001	2002	2003(a)	2003(b)
9/0 non-offset J	8.30	6.91			
9/0 offset J	7.41				
16/0 non-offset circle	5.73	7.49	8.50	8.96	8.45
18/0 non-offset circle		4.66		6.61	7.77
16/0 offset circle			6.83		
18/0 offset circle			8.14		
Japanese tuna hook				10.14	

Data were taken from Bolten et al. (2002) and Bolten and Bjorndal (2003, 2004, 2005). The experimental protocol varied in 2003; see text for detail.

Table 7 – Capture rate (catch per thousand hooks) of blue sharks in the Azores pelagic longline experiments

Treatment	2000	2001	2002	2003(a)	2003(b)
9/0 non-offset J	15.92	30.49			
9/0 offset J	13.03				
16/0 non-offset circle	17.29	55.10	95.47	36.51	53.77
18/0 non-offset circle		50.23		35.19	51.10
16/0 offset circle			76.04		
18/0 offset circle			90.26		
Japanese tuna hook				25.71	

Data were taken from Bolten et al. (2002) and Bolten and Bjorndal (2003, 2004, 2005). Blue sharks were targeted in 2001, 2002, and 2003, but not in 2000. The experimental protocol varied in 2003; see text for detail.

spects, the experimental protocol used in the Azores (single bait and hook type alternated within each set) was superior to that employed in the NED. As noted above, however, it is unfortunate that the prevalent hook type used in the Azores was not employed as a control.

The approach taken in the Azores was quite different than that employed in the NED experiments. In the Azores, a single vessel was chartered to conduct the experiment. This provided an effective, but very different, incentive than that employed in the NED experiment. The work in the Azores was designed with the participation of a group of stakeholders, including commercial fishermen (Bolten et al., 2000). A power analysis (Wetherall, 2000) was conducted prior to the commencement of the experiment; the results of this analysis improved the eventual experimental design. And, as was the case in the NED, the CPUE of loggerhead turtles in the Azores longline fishery was high enough to allow for effective experimentation.

From the four years of experimentation in the Azores, we can conclude:

1. The use of circle hooks did not result in a decrease in the capture rate of loggerhead turtles when compared with J-hooks, although there was a general trend towards reduced capture rates with large and offset hook types. The use of circle hooks did result in a significant decrease in capture rate of loggerheads compared with Japanese tuna hooks in a brief trial conducted in 2003.
2. The use of circle hooks resulted in a large (47%) and significant reduction in the proportion of loggerhead turtles hooked in the throat rather than in the mouth. This difference is likely to lead to a significant reduction in post-hooking mortality.
3. There was considerable inter-annual variation in the capture rates of loggerhead turtles over the three years of the experiment. Some of this variation may have been caused by a shift in target species from 2000 to 2001.
4. It is not possible to draw conclusions regarding the effect of circle hooks on the capture rate of target species (swordfish and blue sharks) in this fishery.
5. It is not possible to draw conclusions regarding the effect of circle hooks on the by-catch of other non-target species in this fishery.

4. Experiments in the Gulf of Mexico

The US pelagic longline fishery also operates in the Gulf of Mexico, where both swordfish and yellowfin tuna (*Thunnus albacares*) are targeted. Tuna are captured by vessels using circle hooks baited with fish in daytime sets, while other vessels capture swordfish on J hooks baited with squid during overnight sets. This is the only area where the US Atlantic pelagic longline fleet used circle hooks routinely prior to the NED experiment. Both leatherback and loggerhead turtles are taken, but in recent years the number of leatherbacks captured has increased and now exceeds the number of loggerheads taken (Garrison, 2005). This trend is correlated with an increase in the number of sets directed at swordfish using J hooks and squid and a decrease in the number of tuna sets using circle hooks and fish bait (Garrison, 2003).

Garrison (2003) used data collected by NMFS observers to examine fishing practices, capture rates of turtles and target species, and the effect of hook and bait type on these capture rates for the Gulf of Mexico. In total, 1729 longline sets were observed in the Gulf of Mexico between 1992 and 2002. Most of these sets (76%) used J-hooks, but a substantial proportion (19%) employed circle hooks, with a few sets (5%) using both hook types. Hooks of both types were smaller than those employed in the NED experiment. The circle hooks employed were typically 16/0 and the J-hooks used were 7/0 or 8/0. A qualitative comparison revealed that sets using J-hooks experienced higher catch rates of turtles than those with circle hooks, although this comparison is confounded by other concomitant differences in fishing practices (see below). No loggerheads were observed captured on sets that employed circle hooks.

Garrison concluded that, in general, the patterns observed in the Gulf of Mexico were consistent with the results of the NED experiment (Watson et al., 2005), but that specific inferences were limited by the confounding effects of set type (swordfish or tuna). In particular, because tuna sets (using circle hooks) are fished during the day while swordfish sets (using J-hooks) are fished at night, it is impossible to draw conclusions regarding the effect of hook type on capture rate of turtles. In addition, the strong association between hook and bait type, in which squid is typically used with J-hooks and fish bait used with circle hooks, precludes any meaningful analysis of the effect of bait type on the capture rate of turtles. No data were presented on the effect of hook or bait type on hooking location.

To determine the efficacy of large (18/0) circle hooks in the directed yellowfin tuna fishery in the Gulf of Mexico, the National Marine Fisheries Service conducted an experiment in early 2004. The experiment was designed to examine the fishing efficiency of 18/0 circle hooks and to collect data on the capture rates of turtles with this gear type (Watson et al., 2004b).

4.1. Experimental design

The control treatment was a non-offset 16/0 circle hook, the predominant hook type used in the directed tuna fishery in the Gulf of Mexico (Garrison, 2003). The experimental treatment was an non-offset 18/0 circle hook, the same hook (C_1)

used in the 2002 and 2003 NED experiments. The two hook types were alternated along the mainline, with an odd number of hooks between floats, so that the position of each hook type varied with respect to float position. All hooks were baited with sardines and each participating vessel was required to conform to a set of standardized fishing practices (Table 1 in Watson et al., 2004b). A NMFS observer was aboard each vessel to record catches and provide oversight of fishing operations. This is a simple and quite powerful design.

4.2. *Analysis*

This work has not yet been fully analyzed and, to date, only summary results are available. Watson et al. (2004b) presented the results of paired *t*-tests examining differences in the number and weight of yellowfin tuna captured on the two hook types. The report notes that these results are consistent with those from a modeling exercise in which total catch was the dependent variable and the number and type of hooks were the independent variables (Watson et al., 2004b), although no details of this work are presented in the report.

4.3. *Results*

The results of this experiment are presented in Watson et al. (2004b) and summarized in Table 1. Only three leatherbacks were captured; two turtles on 18/0 circle hooks (0.135/1000 hooks) and one on a 16/0 hook (0.068/1000 hooks). All three turtles were foul hooked and released alive. These low capture rates were insufficient to allow for any analysis of the effect of hook size on turtle capture rates.

There were significant reductions in both the number ($p = 0.0025$) and weight ($p = 0.0183$) of tuna caught on the 18/0 circle hooks. Both the number and marketable weight of tuna captured on the larger hooks was reduced by 26% when compared to the control treatment. There were no reports of catch rates for non-target species, other than turtles.

4.4. *General conclusions*

This was a very modest experiment, with a relatively small number of hooks fished in a simple protocol. To place this experiment in context, the Gulf of Mexico trial employed only 3% of the total number of hooks used in the NED experiment (Watson et al., 2005). The experimental design was straightforward and only a single treatment was evaluated. Care was taken to control potentially confounding factors. No power analysis was presented and the authors note that the CPUE of leatherbacks in the experiment was much lower than the values observed in the Gulf of Mexico during 2002 (Garrison, 2003) or in the NED experiment (Watson et al., 2005).

From the results of this experiment we can conclude that:

1. Too few turtles were captured to determine whether or not the use of 18/0 circle hooks will reduce the capture rates of leatherback turtles in the Gulf of Mexico tuna longline fishery.
2. The use of 18/0 circle hooks results in a significant reduction in the catch rates of yellowfin tuna, when compared to the standard 16/0 circle hook.

5. Experiments in Ecuador

A large-scale program to test circle hooks in the artisanal longline fisheries along the Pacific coast of the Americas has been initiated by governmental agencies, inter-governmental organizations, and non-governmental organizations. The effort has been spear-headed by an initiative in Ecuador (Largarcha et al., 2005). The goal of the program is to test the efficacy of circle hooks as a means of reducing the mortality of turtles in these longline fisheries, while assessing the economic viability of these hooks in the artisanal longline fisheries of the region.

There are two major fisheries for the artisanal longline fleet in Ecuador: a warm-water (November to April) fishery for mahi-mahi (*Coryphaena hippurus*) and a cold-water (May to October) fishery for bigeye tuna. Many other fish species are taken and retained in both fisheries; very little is discarded. Fishing in both seasons takes place primarily during daylight hours, although 20% of sets in the tuna fishery occur at night. The most common hook used in the tuna fishery is a 9/0 or 10/0 Japanese tuna hook. In the mahi-mahi fishery, 4/0 or 5/0 J hooks or 7/0 Japanese tuna hooks are commonly employed.

The nature of the Ecuadorian fishery is different from that of the US Atlantic pelagic longline fishery or the Azorean fishery in almost all aspects (Largarcha et al., 2005). Typically, a group of two to eleven small (ca. 7.5 m) vessels, referred to as 'fibras' work co-operatively with a larger (ca. 20 m) vessel, known as a 'bote' which acts as a mother ship, providing supplies and storing the catch, throughout a trip. Trips can last between 9 and 17 days, depending on the season and target species.

5.1. *Experimental design*

The experimental program began with a series of workshops to describe the extent of the conservation problem, examine potential solutions and discuss the structure of an experiment. The experiment itself was launched in March 2004. A hook exchange program was initiated in which 2/3 of a vessel's hooks were replaced by circle hooks. Ecuadorian longline fishermen typically employ J-hooks or Japanese tuna hooks of a variety of sizes and configurations. This innovative program led to the participation of 115 vessels by April 2004.

The experimental design was similar in both the tuna and mahi-mahi fisheries. Three hook types were evaluated: a control J-hook and two experimental treatments of circle hooks. Each hook type was alternated along the mainline and each mainline started with a different type of hook (Largarcha et al., 2005). In the tuna fishery, the experimental treatments were 16/0 and 18/0 10° offset circle hooks. In the mahi-mahi fishery, the two treatments were 14/0 and 15/0 non-offset circle hooks.

It was difficult to standardize all aspects of fishing practices employed in this experiment. For example, neither the control J-hooks nor the experimental hooks used in the tuna fishery were standardized; hooks of various material and manufactured by a variety of companies were employed. In addition, it was not possible to standardize bait types across treatments. Nevertheless, care was taken to create as rigorous an experiment as possible.

An observer was placed with each group of fishing vessels, consisting of a bote and several fibras. Typically, two fibras in each group participated in the experiment and the observer rotated between these vessels, recording the capture of turtles and catches of target species. Only data recorded directly by the observers from sets that adhered to the experimental protocol were included in the analysis (Largarcha et al., 2005).

5.2. *Analysis*

To date, preliminary results have been presented from only the first year of this experiment and no detailed statistical analysis is yet available. The preliminary analysis focused only on those trips in which at least one capture was observed. Each treatment was then compared independently against the control in a one-tailed *t*-test to evaluate the hypothesis that the treatments would result in a *reduction* in the capture rate of turtles. For reasons that are not clearly explained, trips were used as the metric of effort, rather than sets. The set is a more appropriate experimental unit and use of this effort metric would result in increased statistical power. In addition, each trip did not have an equivalent number of sets, nor are trips corrected for variation in the number of sets. In general, the analytical approach used here is somewhat crude; presumably a more appropriate and sophisticated analysis will be conducted in the future.

5.3. *Results*

Results of the first year of experiments are presented in Largarcha et al. (2005) and summarized in Table 1. A large number of observations were discarded because they did not adhere to the experimental protocol (typically the requirement for a balanced distribution of the three hook types along the mainline). Some turtles were entangled, but not hooked, in both fisheries; these turtles were not included in the analysis.

In the tuna fishery the use of 16/0 circle hooks reduced the capture rates of sea turtles (all species combined) by 44% and the use of 18/0 circle hooks reduced the capture rate by 89% (Table 8). Considering only the daytime fishery (80% of sets), the capture rates were reduced by 60% and 87%, respectively (Largarcha et al., 2005). The results of the paired *t*-tests contrasting each treatment with control hooks were not significant for the 16/0 circle hooks ($p = 0.139$), but were significant for the 18/0 circle hooks ($p = 0.019$).

No statistical comparisons were made for turtle CPUE in the mahi-mahi fishery due to the relatively small sample of observed sets. The 14/0 circle hooks resulted in a reduction of sea turtle CPUE by 37% compared to control hooks; the 15/0 hooks reduced turtle CPUE by 17% (Table 9). Capture rates on control hooks in the mahi-mahi fishery were very high (2.2 turtles per thousand hooks).

Table 8 – Capture rates (turtles or fish per thousand hooks) in the Ecuadorian experimental fishery for tuna

Treatment	Turtles	Target
Control J hook	1.36	13.9
10° offset 16/0 circle hook	0.76	13.0
10° offset 18/0 circle hook	0.15	12.6

Data were taken from Largarcha et al. (2005).

Table 9 – Capture rates (turtles or fish per thousand hooks) in the Ecuadorian experimental fishery for mahi-mahi

Treatment	Turtles	Target
Control J hook	2.20	149.8
14/0 straight circle	1.38	104.9
15/0 straight circle	1.83	96.3

Data were taken from Largarcha et al. (2005).

Observers were able to document the hooking location in 14 turtles in the tuna fishery and 57 turtles in the mahi-mahi fishery. There was a significant reduction in the proportion of turtles that swallowed the hook when 16/0 circle hooks were compared to J-hooks in the tuna fishery; only a single turtle was captured on an 18/0 circle hook. A stronger signal was observed in the mahi-mahi fishery, in which significant reductions occurred in the proportion of turtles that swallowed either 14/0 (96%) or 15/0 (53%) circle hooks.

The use of circle hooks resulted in a slight reduction of the CPUE (number of fish per thousand hooks) of target species in the tuna fishery (Table 8). The CPUE was reduced by 6.1% on 16/0 circle hooks and 9.5% on 18/0 circle hooks; neither value was significantly different than that observed on control hooks. Catch rates of target species in the tuna fishery were perceived to be relatively low by participants, so the results may not be representative of the fishery (Largarcha et al., 2005). In contrast, catch rates of target species in the mahi-mahi fishery were reduced by 30% on 14/0 and by 36% on 15/0 circle hooks (Table 9). Statistical tests of these latter contrasts were not conducted. Participating fishermen were willing to absorb the slight reduction in tuna catches, but not the large reduction in catches of mahi-mahi.

Very few (less than 0.1% by number) of captured fish are discarded in these fisheries. Largarcha et al. (2005) presented summaries of the catch rates for all species taken frequently in both the tuna and mahi-mahi fisheries, but did not examine whether or not differences in catch rates due to hook type were statistically significant.

5.4. *General conclusions*

The work in Ecuador is particularly important because it focuses on fisheries that are representative of many of the world's artisanal longline fleet. These fisheries are common in tropical and sub-tropical latitudes and likely kill very large numbers of turtles. The most important conclusion from this study is that it is possible to conduct controlled experiments in artisanal longline fisheries. This work, including the educational and outreach components, holds many lessons for other workers contemplating such trials.

The authors of the report recognize that much work remains, including: further field trials; alternative hook types (including circle hooks manufactured from various materials); continued discussion with fishermen regarding the design, implementation and interpretation of field trials; and a more sophisticated statistical analysis. Trials are now being expanded into adjacent waters (e.g. Valqui et al., 2006).

In general, however, the conclusions drawn from the first year of experimentation in Ecuador regarding the effects of circle hooks are broadly similar to those drawn from other trials. The primary exception to this finding was that dramatic reduction of mahi-mahi catches, indicating that these hooks are not a useful mitigation strategy for this fishery. In summary:

1. The use of circle hooks resulted in a large and significant reduction in the capture rate of sea turtles in the tuna fishery. Large circle hooks resulted in a greater reduction in CPUE than smaller circle hooks. The reductions in turtle capture rates due to the use of circle hooks in the mahi-mahi fishery were considerably more modest.
2. The use of circle hooks in both fisheries resulted in a very large and significant reduction in the proportion of turtles that swallowed the hook. This reduction would likely lead to a very large reduction in the post-release mortality rate of captured turtles, assuming that safe de-hooking and release protocols are followed.
3. The use of circle hooks resulted in a small and non-significant reduction in the catch of target species in the tuna fishery. In the mahi-mahi fishery, the use of circle hooks resulted in a large (ca. 30%) reduction in the catch of target species. Thus, the circle hooks evaluated in these trials have commercial potential in the tuna fishery (particularly the 16/0 hook) but not in the mahi-mahi fishery.
4. No statistical analyses were conducted to examine the effects of hook type on catch rates of other species.

6. Discussion

The studies reviewed here employed more than a million and a half hooks in five distinct fisheries (Table 1). The NED trial dominated both the number of sets and number of hooks fished and is the only one to have been fully analyzed and peer-reviewed (Watson et al., 2005).

The results of these experiments are summarized in Table 10 in terms of their success in: reducing capture rate; reducing post-release mortality; and in maintaining an economically viable fishery. (I assume that a reduction in the number of turtles ingesting hooks will lead to a concomitant reduction in mortality following release). Four of the five fisheries experienced a significant reduction in capture rate and/or post-release mortality, indicating that circle hooks would reduce overall mortality. Only in the Gulf of Mexico trial, in which only three turtles were captured, was there no reduction in either capture rate or post-release mortality. However,

Table 10 – Summary of findings from experimental trials designed to assess the efficacy of circle hooks a means of reducing sea turtle mortality in pelagic longline fisheries

Fishery	Reduction in capture rate	Reduction in mortality	Economically viable
NED	Yes	Yes	Yes
Azores	Yes[a]	Yes	Yes
Gulf of Mexico	?	?	?
Ecuador – Tuna	Yes	Yes	Yes
Ecuador – Mahi	?	Yes	No

a The use of circle hooks in the Azores resulted in a significant reduction in capture rate in only one of four years of trials.

in only three of the five fisheries (NED, Azores and Ecuadorian tuna) were all three criteria met and in one of these cases (the Azores), significant reductions in capture rate were seen in only one of four years. Furthermore, in one fishery (Ecuadorian mahi-mahi), circle hooks reduced catches of target species to such a degree that their use was impractical.

I conclude, therefore, that circle hooks have the potential to reduce the mortality of sea turtles captured in pelagic longline fisheries, but that they should be field tested in a rigorous experiment before they are required or employed in any fishery. Circle hooks will not reduce sea turtle mortality in every pelagic longline fishery; each case needs to be tested prior before this conservation measure is adopted.

Furthermore, in some cases the use of circle hooks may reduce turtle mortality by changing hooking location instead of decreasing capture rate, particularly for loggerheads. Such a change will obviously be of greatest benefit in fisheries where participants adhere to best practices for handling and release (Epperly et al., 2004). This finding also underscores the need for further work to assess the survival of turtles after release. The use of satellite-linked telemetry to monitor post-release survival has been controversial (Chaloupka et al., 2004a; Hays et al., 2004; Chaloupka et al., 2004b), largely because it is difficult to differentiate mortality from other possible causes of transmission failure. It is critical to resolve this problem so that we can derive empirical estimates of post-release survival under various conditions (such as after capture with different hook types).

Circle hooks reduce turtle mortality because of their shape and size (Gilman et al., 2005). The barb of circle hooks is pointed back towards the shaft of the hook itself; this shape results in fewer and less dangerous captures than J hooks. In addition, there are clear trends towards lower capture rates with the use of larger hooks in experiments with captive turtles (Watson et al., 2003b). Larger (wider) hooks have a lower probability of ingestion and capture by a turtle feeding on bait, because the hooks are wider than the gape of the turtle. From the perspective of turtle conservation, there is a clear benefit to using large hooks, although this benefit must be weighed against potential reductions in the catch rate of target species. In addition, such benefits may be limited primarily to turtle species, such as loggerheads, that consume bait.

Complicating the assessment of circle hooks is a bewildering variety of hook types that differ in shape, width, orientation of point, and material (Gilman et al., 2006). This variation was noted as a problem in interpreting results of the Ecuadorian experiment (Largarcha et al., 2005). As noted above, width is clearly a critical parameter, but it is likely that other aspects of the hook are important factors influencing capture rates of both turtles and target species. A standardization of terminology and measurement protocols for various hook types is urgently needed (Yokota et al., 2006).

The use of circle hooks may either reduce or increase the catch of target species. In some cases, there were modest increases in the CPUE of target species when certain combinations of hooks and bait were used. In other cases, such as the experiment with the Ecuadorian mahi-mahi fishery, circle hooks reduced catches to such an extent that their use was impractical. When considering the practicality of implementing a mitigation measure, such as circle hooks, it is important to consider the *net* costs and benefits. Fishermen may be willing to accept a modest decrease in the capture rates of target species from the use of circle hooks, if this gear modification allows them to fish in an area that would otherwise be closed. Such a decrease in CPUE may also be offset by an increase in fishing efficiency caused by a decreased number of interactions with turtles and other protected species. A reduction in CPUE may also be partially offset by an increase in the value of retained target catch, if fish are kept alive longer on circle hooks due to a change in hooking location (N. Beideman, Blue Water Fishermen's Association, personal communication).

At the present time, it is not possible to draw any broad conclusions regarding the effects of circle hooks on the by-catch of other species. There have been no analyses of the effects of circle hooks on catches of marine mammals or sea birds due to their very low capture rates in fisheries examined to date (see, for example, Yeung, 2001 and Garrison, 2005). A recent analysis of an experimental Japanese North Pacific longline fishery found no effect of circle hooks on the capture rate of blue sharks (Yokota et al., 2006). Further analyses should be conducted to examine the potential effects of circle hooks on non-target species and to ensure that their use does not have adverse consequences for other taxa.

Watson et al. (2005) also concluded that circle hooks may not be effective in all areas and for all target species. This caveat is underscored by the significant inter-annual variation observed in the multi-year experiments in the NED and Azores. Despite their intuitive simplicity, pelagic longline fisheries are complex enterprises. Catch rates of target and non-target species are affected by a myriad of factors, including time of day fished, soak time, depth fished, bait type and size, the use of attractors (light sticks), temperature, location and season (Gilman et al., 2006). These factors interact in a complicated and sometimes unpredictable manner. The design of the hook is only one factor that affects catch rates. A particular factor to consider when evaluating the potential efficacy of circle hooks is the size of the turtles taken as by-catch, especially in relation to the size of the target species. In this regard observations of the feeding behavior of captive turtles in relation to hook size are particularly useful.

Furthermore, it is not possible to predict what reduction in catch rate or what change in hooking location may result from the use of circle hooks in a fishery. Managers, fishermen and other stakeholders need to contrast the potential for mortality reduction offered by circle hooks with that of other mitigation measures. The only way to determine what level of mortality reduction will be achieved by circle hooks is to conduct fishery trials.

It is important to consider the use of circle hooks in the context of other potential mitigation measures. Circle hooks are only one of the methods currently available in the conservation tool box. Their use may will not be practical, desirable, or effective in all circumstances, and managers, scientists and fishermen should continue to strive for additional means of reducing sea turtle mortality in pelagic longline fisheries. There is considerable promise in pursuing other operational solutions, such as modifying the depth and duration of sets, and in encouraging vessels to move locations after capturing a turtle (see Gilman et al., 2006).

In addition to an experimental evaluation of their efficacy, there are other important reasons for conducting field trials before implementing the use of circle hooks. Fishermen need to evaluate the practicality of using these hooks in their fishery. To be fully adopted, mitigation measures must be practical and perceived to be economically viable by fishery participants (Gilman et al., 2006). Ultimately, circle hooks will be judged as useful or not by fishermen, and their diffusion into pelagic longline fisheries will depend on the attitudes of these individuals. As noted above, fishermen must evaluate the net costs and benefits of this conservation measure; effective solutions will reduce the mortality of sea turtles and improve the livelihoods of fishermen. Field experiments provide an excellent opportunity for evaluation by the fleet.

It may be argued that experiments are too costly or complex to conduct each time that circle hooks are contemplated as a conservation measure. Certainly there will be few opportunities to conduct experiments at the scale and cost of those carried out in the western North Atlantic. Fortunately, the experiments in Ecuador offer an excellent model of relatively low-cost field trials that could be emulated in many areas. The principal investigators of these trials have gone to great lengths to work directly with fishermen at every stage (Largarcha et al., 2005); such interactions are critical for the success of any field experiment.

Researchers, managers and fishermen interested in conducting such trials will find much to learn from the experiments reviewed here. Any experimental approach to by-catch mitigation should consider the following:

1. Recognize that fishermen need to be motivated to participate in an experiment. Such motivation may come from the profit of a vessel charter, the opportunity to fish in a closed area, or fear of more draconian conservation measures.
2. It is critical to work closely with the fishery prior to, during and after the conclusion of any trial. The success of any trial and eventual implementation of a conservation measure ultimately depends on fishery participants.
3. Conduct a power analysis prior to field work to ensure that a statistically significant outcome is feasible given the observed variation in capture rates and level of effort.

4. Maximize statistical power by minimizing the number of experimental treatments and ensure that a consistent control treatment is used in each trial.
5. Minimize variation in fishing practices (e.g. number of hooks per set, the use of light sticks, bait type, etc.) to reduce the effects of confounding factors.
6. Conduct experiments in times and areas where by-catch rates are high, to maximize statistical power and reduce the number of sets required to demonstrate a result.
7. Use independent observers to record data on the capture rates of target and non-target species and on fishing practices employed in the experiment.
8. Consider the ethical implications of any experiment beforehand. In some cases, for example, it may not be appropriate to test a potential conservation measure on a gravely endangered population. In such cases, proxy populations or fisheries may be available.

In conclusion, circle hooks offer a potentially effective means of reducing the mortality of sea turtles in pelagic longline fisheries, either by reducing the capture rate, the post-capture mortality rate, or both. Due to the variation in fishing practices and in the complex dynamics of turtle capture, however, circle hooks should be field tested in a rigorous experiment before they are employed in any fishery.

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