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Review of effects of pelagic longline hook and bait type on sea turtle catch rate, anatomical hooking position and at-vessel mortality rate

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REVIEWS

Review of effects of pelagic longline hook and bait type on sea turtle catch rate, anatomical hooking position and at-vessel mortality rate

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Abstract Bycatch in pelagic longline fisheries is one of the most serious threats to some sea turtle populations. Hook shape, hook minimum width and bait type have been the focus of research and management measures to mitigate problematic bycatch of vulnerable taxa. To assess the current state of knowledge and progress over the past decade, we reviewed findings on the effects of hook and bait type on pelagic longline sea turtle catch rates, anatomical hooking position and at-vessel mortality. Fish versus squid for bait lowered catch rates of leatherback sea turtles (*Dermochelys coriacea*) and individual species of hard shelled turtles. Fish bait also reduced hard-shelled turtle deep hooking. Wider circle hooks reduced both leatherback and hard-shelled turtle catch rates relative to narrower J and tuna hooks, and reduced the proportion of caught hard-shelled turtles that were deeply hooked. Wider circle hooks with fish bait reduced leatherback and hard-shelled turtle catch rates relative to narrower J and tuna hooks with squid bait. Wider versus narrower circle hooks reduced hard-shelled sea turtle catch rates and deep hooking. The mechanisms for hook and bait type effects on turtle interactions are reviewed. Research designed to assess single factor effects is needed, in particular for hook shape and minimum width, and for hook and bait effects on anatomical hooking position and survival rates. Fishery-specific and holistic assessments are needed to account for variability between fisheries in a bycatch mitigation method's commercial viability, relative risks to affected populations and possible conflicting effects on vulnerable taxa.

Keywords Bycatch · Circle hook · Longline fisheries · Sea turtle

Introduction

Of the seven extant species of sea turtles, which have all been documented to interact with pelagic longline fisheries, six are categorized as threatened with extinction, and at least five are experiencing decreasing trends in absolute abundance (FAO 2010; IUCN 2016). Bycatch in pelagic longline fisheries is one of the most serious threats to some sea turtle populations (Lewison et al. 2004; Wallace et al. 2011, 2013; IUCN 2016).

There is a growing body of research documenting the efficacy of methods involving changes in fishing methods and gear at reducing sea turtle catch rates and

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injury. These include, for example, setting gear below prime sea turtle vertical habitat, not using chemical or electrical light sticks, adjusting the time of day of fishing operations, reducing gear soak duration, single- versus multiple-hooking bait, and not fishing in spatio-temporally predictable bycatch hotspots (Beverly and Chapman 2007; Gilman et al. 2006; Clarke et al. 2014; Gilman and Hall 2015; Huang et al. 2016). Hook shape, hook narrowest (minimum) width and bait type also can significantly affect sea turtle catch rates and injury. These latter three variables have been the focus of research and management measures to mitigate unwanted bycatch of sea turtles, seabirds, marine mammals, elasmobranchs and some teleosts (Clarke et al. 2014; Gilman et al. 2014). Additionally, these three factors may result in cross-taxa conflicts; i.e., hook and bait combinations that reduce sea turtle catch and injury in pelagic longline fisheries may exacerbate interactions with other at-risk taxa (Gilman et al. 2016).

Gilman et al. (2006) conducted the first review of research on mitigating sea turtle bycatch in pelagic longline fisheries. At this time, there were a small number of studies conducted in a small number of fisheries with relatively small sample sizes, and few studies were designed to assess single factor effects as they had simultaneous variability in multiple potentially significant explanatory variables. The current study aimed to assess progress over the past decade since the initial literature review and pioneering research by Watson et al. (2005) and Bolten and Bjorndal (2006), to determine the current state of knowledge on the effects of hook shape, hook minimum width, bait type, and combinations of these factors, on pelagic longline sea turtle catch rates, anatomical hooking position and at-vessel mortality.

Hooking location provides an indicator of the degree of injury and concomitant probability of survival. Externally hooked organisms have been observed to have a higher haulback survival rate and may have a higher probability of pre-catch and post-release survival relative to those that are deeply hooked (Chaloupka et al. 2004; Cooke and Suski 2004; Casale et al. 2008; Pacheco et al. 2011; Swimmer and Gilman 2012; Gilman et al. 2013). Haulback, or at-vessel, survival, refers to organisms that are alive when retrieved onboard; pre-catch survival refers to organisms that, e.g., escape from the gear or are released alive by crew from the gear in the water and are not brought onboard, and survive the interaction; and post-release survival refers to organisms that are retrieved onboard and returned to the sea alive and survive the interaction (ICES 1995; Gilman et al. 2013). In fisheries where fishers routinely retrieve hooks from turtles, hook removal from deeply-hooked turtles is more likely to be lethal than removal from externally- and mouth-hooked turtles (Parga et al. 2015). However, when best practice handling and release practices are employed, such as removing as much trailing line as possible, both deeply and non-deeply hooked turtles released with a retained hook have been observed to survive (Mangel et al. 2011; Parga 2012; Swimmer and Gilman 2012; Swimmer et al. 2014). Haulback disposition enables an assessment of the effect of combinations of gear components on mortality rates and an indication of pre-catch and post-release probability of mortality.

This study was recommended at the 2016 Workshop on Joint Analysis of Sea Turtle Mitigation Effectiveness (WCPFC and SPC 2016) to support a project of the Areas Beyond National Jurisdiction Tuna Project being implemented by the Western and Central Pacific Fisheries Commission and the Pacific Community.

Methods

Both structured and unstructured literature searches were conducted following methods described by Gilman et al. (2016). Findings were compiled on sea turtle species-specific statistically significant single factor effects of hook shape, hook minimum width, bait type, and of combinations of these three factors, on catch rate, proportion deeply hooked, and at-vessel mortality rate. Findings of no significant effect of the three single factors were also compiled for records with a minimum of 10 species-specific observations.

Four predominant hook shapes used in pelagic longline fisheries are circle, J, tuna and teracima (Beverly 2009). Studies compiled for this study used the former three hook shapes (Fig. 1). Hook minimum or narrowest width refers to the narrowest dimension of the hook (Fig. 2) (Curran and Bigelow 2011; Serafy et al. 2012). Bait types were squid species (*Illex sp.*) versus relatively small species of fish, including pelagic 'forage' fishes such as mackerels and species with mackerel-like characteristics, including, for

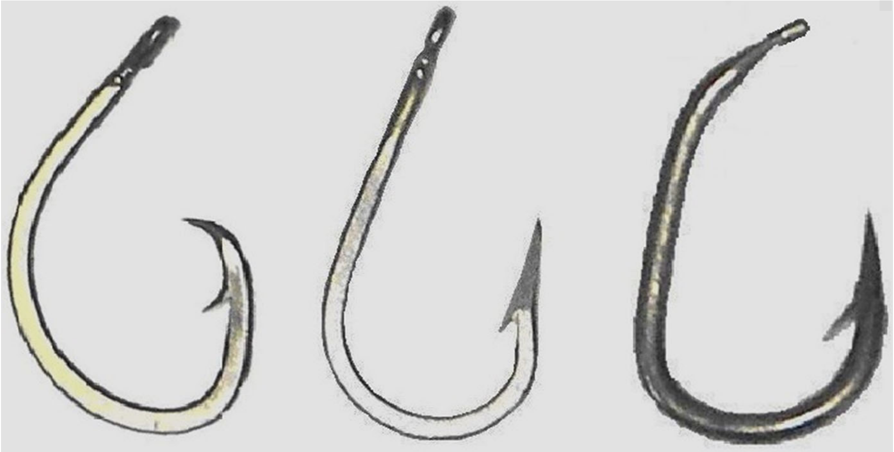

Fig. 1 From *left*, circle, J and tuna hooks, three hook shapes commonly used in pelagic longline fisheries

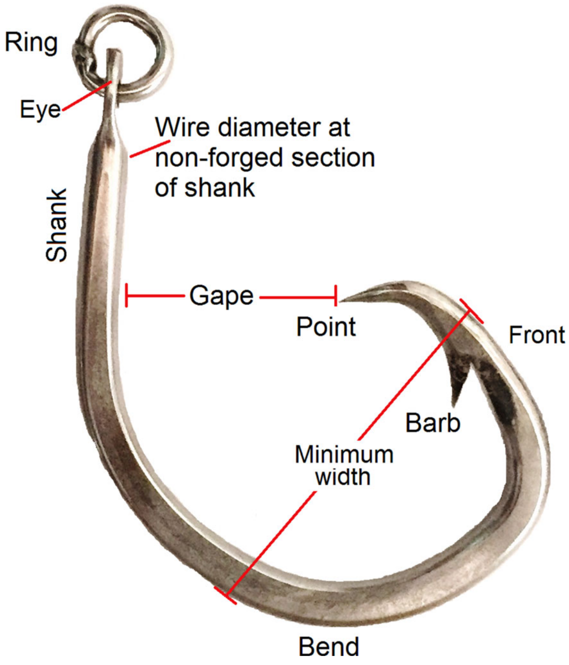

Fig. 2 Hook minimum width and other main elements of a fishing hook (Curran and Bigelow 2011; Serafy et al. 2012). The part of the hook with the narrowest width varies by hook type as well as, to a smaller degree, for hooks of the same hook manufacturer and size

example, sardines (*Sardinops* spp.) and saury (*Cololabis sairi*) (Collette and Nauen 1983). Deeply hooked turtles are those that are internally hooked versus hooked externally or in the mouth. At-vessel or haulback condition refers to whether the turtle was alive versus dead when brought to the vessel before being handled by crew.

The following definitions are employed hereafter for the terms 'finding', 'record', 'study' and 'publication'. A 'finding' is one result of a significant difference of one single factor or combination of factors on the catch rate, haulback survival rate or proportion of catch that was deeply hooked for a single sea turtle species. A 'record' is a set of significant findings of the effects of a single factor or combination of factors resulting from one discrete study, where one record may include multiple findings. A 'study' is a single controlled or comparative at-sea experiment, controlled or comparative experiments of captive sea turtles, or analysis of observer program data that assessed the effect of one or more of the focal factors, where one study may have produced multiple records. And, a 'publication' is a single publication or grey literature document, where one publication or document may report multiple records and findings from one or more studies.

Results

Table 1 summarizes the number of findings of statistically significant effects of individual factors hook shape, hook width and bait type, and combinations of factors on individual sea turtle species' catch rates, haulback survival rates and proportion of catch that was deeply hooked. Species-specific significant findings were found only for the factors and combinations of factors shown in Table 1. The findings on hook minimum width were all from comparisons of different sizes of circle hooks. The findings on bait type

Table 1 Number of findings of statistically significant increases and decreases in individual sea turtle species' catch rates, haulback survival rates and proportion of catch that was deeply hooked, by individual and combinations of pelagic longline gear factors. Values in parentheses are the number of findings from experiments without simultaneous variability in two or more of the gear factors hook shape, hook narrowest width and bait type

Species	Catch rate		Proportion deeply hooked		Haulback survival rate	
	Higher	Lower	Higher	Lower	Higher	Lower
Larger hook minimum width[a]						
Green		1				
Loggerhead		1 (1)		1 (1)		
Olive ridley		1				
Fish versus squid for bait[b]						
Leatherback		5 (5)				
Loggerhead		4 (3)		1 (1)		
Olive ridley		2 (2)		2		
Wider circle versus narrower J hook[c]						
Green		1				
Hawksbill		1				
Leatherback		7				
Loggerhead		5		8	1	1
Olive ridley		4			1	1
Wider circle versus narrower tuna hook[d]						
Green		1				
Loggerhead		1		1		
Olive ridley		2				
Wider circle hook and fish bait versus narrower J hook and squid bait[e]						
Leatherback		5				
Loggerhead		4		1		
Olive ridley		1				

[a] Bolten and Bjorndal (2006), Stokes et al. (2011) and Pacheco (2013)

[b] Watson et al. (2005), Mejuto et al. (2008), Stokes et al. (2011), Foster et al. (2012), Santos et al. (2012, 2013) and Parga et al. (2015)

[c] Watson et al. (2005), Bolten and Bjorndal (2006), Brazner and McMillan (2008), Piovano et al. (2009), Sales et al. (2010), Pacheco et al. (2011), Epperly et al. 2012), Foster et al. (2012), Stokes et al. (2012), Andraka et al. (2013), Pacheco (2013), Santos et al. (2012, 2013) and Coelho et al. (2015)

[d] Bolten and Bjorndal (2006) and Andraka et al. (2013)

[e] Watson et al. (2005), Gilman et al. (2007), Foster et al. (2012) and Santos et al. (2012, 2013)

were from a mix of circle, tuna and J hooks (three findings using only a single size of circle hooks, six using only a single size of J hook, three using a mix of hook shapes and sizes). In Table 1, values shown in parentheses are the number of findings from experiments that did not have simultaneous variability in two or more of the gear factors hook shape, hook narrowest width and bait type, i.e., the number of findings that enable a determination of single factor effects.

Since the review published in 2006, 18 additional publications meeting the study filters (species-specific significant findings of effects of hook and bait type) were identified. A total of 64 sea turtle species-specific statistically significant findings in 25 records from 18 publications, published between 2005 and 2015, were compiled (Table 1). Three publications were from the eastern Pacific Ocean, both at-sea experiments. Eleven were from the Atlantic Ocean, comprised of two analyses of observer data and nine at-sea experiments. One was from an at-sea experiment conducted in the Mediterranean. One was an analysis of observer data from a fishery that overlaps the eastern and western and central Pacific Ocean. And, one publication was from an experiment using captive sea turtles. Sample sizes were relatively large for the majority of records. There was a mean of 579,375 hooks (±199,510 SE, range 30,000 to >3.5 million) for 23 of records from at-sea experiments and analyses of observer program data for which information on the number of hooks included in the sample was available. The mean of sample sizes of caught sea turtles in the 25 records was 295 (±76 SE, range 7–1823). There were findings on five sea turtle species (green *Chelonia mydas*, hawksbill *Eretmochelys imbricata*, leatherback *Dermochelys coriacea*, loggerhead *Caretta caretta*, olive ridley *Lepidochelys olivacea*).

Twelve single-species findings of no significant effect of bait type were identified. Three were on catch rates (two on leatherbacks, one olive ridleys, Mejuto et al. 2008; Coelho et al. 2015), five on the proportion deeply hooked (three on loggerheads, two on leatherbacks, Watson et al. 2005; Epperly et al. 2012; Santos et al. 2013; Coelho et al. 2015), and four on at-vessel mortality rates (three on leatherbacks, one on loggerheads, Gilman et al. 2007; Santos et al. 2013; Coelho et al. 2015). Most of these findings on bait type effect were from studies with simultaneous variability in hook shape and/or hook minimum width. Eight single-species findings of no significant effect of hook minimum width were identified, all from Pacheco (2013). Six were on catch rates (five on olive ridleys, one on greens), and two on the proportion deeply hooked (both on olive ridleys). There was a mean of 154 (±33 SE, range 15–571) sea turtle observations. No non-significant findings were identified on the single factor effect of hook shape.

Discussion

To assess the current state of knowledge and progress over the past decade, we reviewed findings on the effects of hook and bait type on pelagic longline sea turtle catch rates, anatomical hooking position and at-vessel mortality. Now a decade since the publication of pioneering research in this field (Watson et al. 2005; Bolten and Bjorndal 2006), there is a large body of evidence demonstrating that wider circle hooks versus narrower J-shaped hooks and fish versus squid bait reduce hard-shelled and leatherback sea turtle catch rates and deep hooking (Table 1). There remains limited understanding of single factor effects, in particular for hook shape and minimum width, and for hook and bait effects on anatomical hooking position and survival rates. Fishery-specific and holistic assessments are needed to account for variability between fisheries in a bycatch mitigation method's relative risks to affected populations and economic viability to address potential tradeoffs, where methods designed to reduce longline risk to sea turtles may exacerbate risk to other vulnerable taxa (Gilman et al. 2016).

What we know

From the compiled findings, for both hard-shelled and leatherback sea turtles, use of fish versus squid for bait reduced catch rates. Fish bait also reduced hard-shelled turtle deep hooking. Wider circle hooks reduced both leatherback and hard-shelled sea turtle catch rates relative to narrower J-shaped hooks, and reduced the proportion of caught loggerheads that were deeply hooked. Wider circle hooks with fish bait reduced both leatherback and hard-shelled sea turtle catch rates relative to narrower J-shaped hooks with squid bait. Based on a relatively small number of findings, wider versus narrower circle hooks reduced hard-shelled sea turtle catch rates and deep hooking.

What we still do not know—defining research priorities

A limited or lack of information prevented drawing strong conclusions on single factor effects of hook shape and hook minimum width, and on effects of individual or combinations of factors on haulback survival rates. Relative to findings on catch rates, there is also little information on effects on anatomical hooking location. Only four species-specific significant findings were compiled on the single factor effect of hook minimum width and no findings (significant or non-significant) were found on the single factor effect of hook shape. There were also no findings comparing narrower circle hooks to wider J, tuna or teracima hooks.

More research designed to assess single factor effects is needed, in particular on hook shape and minimum width. It is as equally important to publish research results documenting non-statistically significant findings of single factor effects as it is to publish statistically significant results, in particular, to test hypotheses that hook minimum width has little effect on leatherback catch rates, and hook shape does not affect hard shelled sea turtle catch rates, discussed below. Given adequate sample sizes, rigorous meta-analyses to determine the pooled relative risk of sea turtle capture, at-vessel mortality and deep-hooking by hook and bait factors could be conducted. Due to the larger sample size plus the number of studies, correctly designed meta-analyses can provide estimates with increased precision and accuracy over estimates from individual studies, with increased statistical power to detect an effect (e.g., Borenstein et al. 2009).

Mechanisms for hook and bait effects

Hook minimum width

Wider hooks, with a larger minimum width (Fig. 2), are understood to reduce captures and deep hooking of hard-shelled turtles, which tend to get caught by ingesting baited hooks (Witzell 1999; Gilman et al. 2006; Clarke et al. 2014). Hook size may affect the length frequency distribution of the catch, where for some species, larger organisms have higher catch risk on larger hooks, up to a threshold hook size (Cortez-Zaragoza et al. 1989; Ralston 1990; Lokkeborg and Bjordal 1992; Bayse and Kerstetter 2010). For species that tend to be caught by ingesting a baited hook, hooks with a larger minimum width reduce the relative catchability of smaller species and smaller length classes of a species, as the larger the hook, the larger the organism needs to be to fit the hook in its mouth (Yokota et al. 2012). Also, the larger gape of wider hooks may result in a higher probability of the hook point fully penetrating the tissue of the mouth cavity of fish that are large enough to ingest the larger hook, reducing their ability to pull the hook out (Lokkeborg and Bjordal 1992). Larger hooks require a stronger force to fully penetrate the tissue, so that larger species and larger length classes of a species that place more tension on the line when hooked may be more likely to have the point fully penetrate the tissue (Lokkeborg and Bjordal 1992). In addition, larger hooks may be stronger and require a larger force before straightening than smaller hooks and therefore when a large organism is hooked, the probability of straightening the hook and escaping may be higher on smaller hooks (Lokkeborg and Bjordal 1992; Bayse and Kerstetter 2010). Variability in the length frequency of a species that overlaps with a fishery's grounds, the difference between the width of the two hooks being compared, and the difference in the hook widths relative to the species' range of mouth sizes will determine if two hooks of different widths have different catch rates. In general, hook size is more likely to affect catch rates of species with relatively small mouths (Stokes et al. 2011; Gilman and Hall 2015). Hook size has also been hypothesized to affect hooking location: larger hooks may be less likely to be ingested and instead be more likely to foul hook (Stokes et al. 2011).

Hook shape

J-hooks are shaped with the point positioned parallel to the hook shaft. Tuna and teracima hooks have a slightly curved shaft, and like J-hooks, the shaft does not protect the point, and as a result, are categorized as 'J-shaped' hooks (Fig. 1) (Beverly and Chapman 2007; Serafy et al. 2009). Circle hooks are circular or oval shaped, and the point is turned perpendicularly back toward the shank, making the point less exposed relative to J-shaped hooks. The less exposed points of circle hooks reduce the probability of foul-hooking organisms. When ingested, J-shaped hooks tend to result in deep hookings, while circle hooks with little or no offset tend to catch in the corner of the mouth (Cook and Suski 2004; Curran and Beverly 2012; Epperly et al. 2012; Clarke et al. 2014; Parga et al. 2015). Due to the prevalent hooking location, circle hooks might result in higher pre-catch[1] and haulback survival rates, make it easier for crew to remove all terminal tackle, and thus increase the probability of post-release survival for turtles released alive (Chaloupka et al. 2004; Cooke and Suski 2004; Godin et al. 2012; Serafy et al. 2012; Swimmer and Gilman 2012; Parga et al. 2015). Furthermore, due to their

[1] If circle hooks result in higher at-vessel survival rate due to the prevalent anatomical hooking location, then it is likely that the hook will also increase the survival rates of hooked organisms that escaped from the gear.

predominant hooking location, organisms captured on circle hooks that will be handled and released require less handling time, minimizing stress (Cooke and Suski 2004). However, circle hooks are harder to remove and may result in more damage when removed relative to J-shaped hooks that are lodged in the same anatomical location (Santos et al. 2013).

Leatherback sea turtles, which are most frequently caught by becoming foul-hooked on the body and entangled, have been observed to have lower catch rates on circle hooks than on J-shaped hooks, in some cases where the two hook shapes were of a similar size (Table 1). Hook shape, however, likely has nominal effect on catch rates of hard-shelled turtles, which tend to get caught by ingesting the hook regardless of hook shape (e.g., Gilman 2011; Epperly et al. 2012; Clarke et al. 2014). For hard-shelled and leatherback turtles that ingest a hook, circle hooks result in a lower proportion of turtles swallowing the hook deeply, into the esophagus and deeper, and therefore likely result in a higher survival rate relative to J-shaped hooks.

Bait type

Different species and sizes of predatory fish have different prey preferences. These preferences are due to differences in prey chemical components, visual stimuli, and differences in the duration of retention of different bait species on hooks during the gear setting, soaking and retrieval operations. These are possible factors explaining differences in catch rates between pelagic species and between sizes of individual pelagic species on fish versus squid for bait (Lokkeborg and Bjordal 1992; Broadhurst and Hazin 2001; Ward and Myers 2007; Yokota et al. 2009). Hard-shelled turtles may prefer squid to finfish due to natural chemical attractants present in squid (Piovano et al. 2004, 2012).

The observed effect of bait type on sea turtle catch rates may be due in part to the relative difficulty for hard-shelled turtles to remove the bait from the hook. Based on observations of captive loggerhead sea turtles, when foraging on fish bait, turtles tear pieces off in small bites or strip the entire bait from the hook. When squid was used for bait, turtles tended to ingest the entire squid bait and hook in a single gulp (Watson et al. 2005; Kiyota et al. 2005; Stokes et al. 2011). However, multiple-hooked fish bait (vs. single-hooked) may result in interactions more similar to squid bait, where multiple-hooked fish bait may shield the point of the hook, and may shield the turtle from contacting the hook surface point and make it more difficult for turtles to remove from the hook (Watson et al. 2005; Stokes et al. 2011).

Bait type is understood to be a more important factor in affecting catch rates for hard-shelled turtle species than leatherbacks, as, discussed previously, the former tend to get caught by ingesting baited hooks, while the latter tend to become captured via foul-hooking or entanglement.

Some longline vessels use large pieces of meat cut from tuna, sharks, rays or other catch, in some cases used on 'shark lines', branchlines attached directly to floats, which can affect sea turtle interactions relative to using small species of fish or squid for bait. For example, Mejuto et al. (2008) observed higher catch rates of loggerhead and olive ridley sea turtles on pieces of blue shark for bait than with squid or mackerel for bait. Echwikhi et al. (2010) observed significantly lower loggerhead turtle catch rates with pieces of stingray used for bait versus whole mackerel.

Fishery specific and holistic assessments

Bycatch measures prescribed to reduce fishing mortality of one at-risk group may inadvertently exacerbate catch and mortality of other at-risk taxa. For example, while circle hooks and fish bait reduce sea turtle catch and deep hooking relative to J-shaped hooks and squid bait, pelagic longline catch rates of sharks are higher on circle hooks and on fish bait based on a meta-analysis and literature review (Gilman et al. 2016). Due to these potential cross-taxa conflicts, fishery-specific relative risks to affected populations should be assessed holistically, across affected taxa, for individual fisheries to determine which gear designs and fishing methods should be used (Gilman et al. 2016).

Furthermore, a bycatch mitigation method's efficacy and effect size at reducing sea turtle bycatch and injury, and its economic viability, are fishery specific. For example, the effect of hook shape, hook width and bait type on catch, injury and mortality of market and bycatch species depends on the species, age classes and sex ratios of principal market and at-risk species that overlap with a fishery (Stokes et al. 2011; Gilman and Hall 2015). Prescribing a hook minimum width for an individual fishery should account for the size frequency distributions of hard shelled turtles and of principal market species that occur at the fishing grounds.

Conclusions

A decade on since the publication of pioneering research on effects of hook and bait type on sea turtle catch, injury and mortality in pelagic longline fisheries (Watson et al. 2005; Bolten and Bjorndal 2006), there is now strong evidence that wider circle hooks versus narrower J-shaped hooks and fish versus squid bait reduce hard-shelled and leatherback sea turtle catch rates and deep hooking. We remain, however, with limited evidence of single factor effects of hook shape and hook minimum width. This is a research priority. Currently, fishery management authorities making fishery-specific decisions on prescribed hook shape and size must rely on hypotheses of the effect of hook minimum width and hook shape on leatherback and hard-shelled sea turtle catch and injury that are based on the mechanisms causing capture. Research is needed that is designed to test single factor effects of hook size and shape. Results will enable testing the hypotheses that (1) wider hooks reduce captures and deep hooking of hard-shelled turtles, which tend to get caught by ingesting baited hooks, but do not affect catch and hooking position of leatherback sea turtles, which are most frequently caught by becoming foul-hooked on the body and entangled; and (2) circle hooks reduce leatherback captures due to their having less exposed points relative to J-shaped hooks, reducing the probability of foul-hooking, but hook shape has no effect on hard-shelled turtle catch, which tend to ingest hooks regardless of their shape.

In addition to improved understanding of single factor effects to guide bycatch management, improved understanding of the relative effect size of hook shape, hook minimum width and bait type on catch and survival rates of sea turtles and other vulnerable taxa is an additional research priority. For instance, if the effect of bait type on catch rates is much larger for sea turtles than for main shark species caught in pelagic longline fisheries, then, if affected turtle populations are of equal or worse conservation status than affected shark populations, using a small species of fish for bait to provide a large benefit to turtles but small detriment to sharks may be determined to be a suitable tradeoff. Using another hypothetical fishery to further illustrate the importance of understanding single factor effects as well as relative effect size, in a deep-set longline fishery that catches only hard-shelled sea turtles, where almost all caught turtles are dead upon haulback, from having drowned during the gear soak, and that catches species of sharks from populations with a poor conservation status, e.g., are threatened with extirpation, relative to using a circle hook of the same size, use of a J-shaped hook might not affect the hard-shelled turtle catch or survival rates, but may reduce shark catch rates (e.g., if wire leaders are not used) and possibly survival rates.

Hook and bait type have been the focus of regional and domestic management measures to mitigate sea turtle bycatch (FAO 2010; Clarke et al. 2014; Gilman et al. 2014). Given possible cross-taxa conflicts of hook shape and bait type (Gilman et al. 2016), in addition to fishery-specific holistic assessments to account for relative risks to affected populations of these two gear components, managers should make use of a broader range of effective and economically viable methods to mitigate sea turtle bycatch that do not risk exacerbating catch and mortality of other at-risk taxa. These methods include deeper setting, not using chemical or electrical light sticks, adjusting the time of day of fishing operations, reducing gear soak duration, single- versus multiple-hooking bait, and avoiding spatio-temporally predictable bycatch hotspots (Gilman 2011).

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References

Andraka S, Mug M, Hall M et al (2013) Circle hooks: developing better fishing practices in the artisanal longline fisheries of the Eastern Pacific Ocean. Biol Conserv 160:214–223

Bayse S, Kerstetter D (2010) Assessing bycatch reduction potential of variable strength hooks for pilot whales in a western north Atlantic pelagic longline fishery. J N. C. Acad Sci 126:6–14

Beverly S (2009) Longline terminal gear identification guide. Secretariat of the Pacific Community, Noumea

Beverly S, Chapman L (2007) Interactions between sea turtles and pelagic longline fisheries. WCPFC-SC3-EB SWG/IP-01. Western and Central Pacific Fisheries Commission, Kolonia, Federated States of Micronesia

Bolten A, Bjorndal K (2006) Experiment to evaluate gear modification on rates of sea turtle bycatch in the swordfish longline fishery in the Azores—Phase 5. Final Project Report. Archie Carr Center for Sea Turtle Research, University of Florida, Gainesville, Florida, USA

Borenstein M, Hedges L, Higgins J, Rothstein H (2009) Introduction to meta-analysis. Wiley, West Sussex

Brazner J, McMillan J (2008) Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fish Res 91:310–324

Broadhurst M, Hazin F (2001) Influences of type and orientation of bait on catches of swordfish (*Xiphias gladius*) and other species in an artisanal subsurface longline fishery off northeastern Brazil. Fish Res 53:169–179

Casale P, Freggi D, Rocco M (2008) Mortality induced by drifting longline hooks and branchlines in loggerhead sea turtles, estimated through observation in captivity. Aquat Conserv 18:945–954

Chaloupka M, Parker D, Balazs G (2004) Modeling postrelease mortality of loggerhead sea turtles exposed to the Hawaii-based pelagic longline fishery. Mar Ecol Prog Ser 280:285–293

Clarke S, Sato M, Small C, Sullivan B, Inoue Y, Ochi D (2014) Bycatch in longline fisheries for tuna and tuna-like species: a global review of status and mitigation measures. FAO Fisheries and Aquaculture Technical Paper 588. Food and Agriculture Organization of the United Nations, Rome

Coelho R, Santos M, Fernandez-Carvalho J, Amorim S (2015) Effects of hook and bait in a tropical northeast Atlantic pelagic longline fishery: part I—incidental sea turtle bycatch. Fish Res 164:302–311

Collette B, Nauen C (1983) Scombrids of the world: an annotated and illustrated catalogue of tunas, mackerels, bonitos and related species known to date. FAO Fisheries Synopsis No 125, vol 2. Food and Agriculture Organization of the United Nations, Rome

Cooke S, Suski C (2004) Are circular hooks and effective tool for conserving marine and freshwater recreational catch-and-release fisheries? Aquat Conserv: Mar Freshw Ecosyst 14:299–326

Cortez-Zaragoza E, Dalzell P, Pauly P (1989) Hook selectivity of yellowfin tuna (*Thunnus albacares*) caught off Darigayos Cove, La Union, Philippines. J Appl Ichthyol 1:12–17

Curran D, Beverly S (2012) Effects of 16/0 circle hooks on pelagic fish catches in three South Pacific albacore longline fisheries. Bull Mar Sci 88:485–497

Curran D, Bigelow K (2011) Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery. Fish Res 109:265–275

Echwikhi K, Jribi I, Bradai M, Bouain A (2010) Effect of type of bait on pelagic longline fishery-loggerhead turtle interactions in the Gulf of Gabes (Tunisia). Aquat Conserv: Mar Freshw Ecosyst 20:525–530

Epperly S, Watson J, Foster D, Shah A (2012) Anatomical hooking location and condition of animals captured with pelagic longlines: the grand banks experiments 2002–2003. Bull Mar Sci 88:513–527

FAO (2010) Guidelines to reduce sea turtle mortality in fishing operations. In: Gilman E, Bianchi G (ed) FAO technical guidelines for responsible fisheries, ISBN 978-92-106226-5. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/docrep/012/i0725e/i0725e.pdf, Accessed 1 April 2016

Foster D, Epperly S, Shah A, Watson J (2012) Evaluation of hook and bait type on the catch rates in the western north Atlantic ocean pelagic longline fishery. Bull Mar Sci 88:529–545

Gilman E (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. Mar Policy 35:590–609

Gilman E, Hall M (2015) Potentially significant variables explaining bycatch and survival rates and alternative data collection protocols to harmonize tuna rfmos' pelagic longline observer programmes. Appendix 1 to WCPFC-SC11-2015/EB-IP-05. Western and Central Pacific Fisheries Commission, Kolonia, Pohnpei, Federated States of Micronesia https://www.wcpfc.int/system/files/EB-IP-05%20LL%20Obs%20bycatch%20data%20fields%20Rev%201%2028%20July.pdf. Accessed 1 Oct 2015

Gilman E, Zollett E, Beverly S, Nakano H, Shiode D, Davis K, Dalzell P, Kinan I (2006) Reducing sea turtle bycatch in pelagic longline gear. Fish Fish 7:2–23

Gilman E, Kobayashi D, Swenarton T, Brothers N, Dalzell P, Kinan I (2007) Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. Biol Conserv 139:19–28

Gilman E, Suuronen P, Hall M, Kennelly S (2013) Causes and methods to estimate cryptic sources of fishing mortality. J Fish Biol 83:766–803

Gilman E, Passfield K, Nakamura K (2014) Performance of regional fisheries management organizations: ecosystem-based governance of bycatch and discards. Fish Fish 15:327–351

Gilman E, Chaloupka M, Swimmer Y, Piovano S (2016) A cross-taxa assessment of pelagic longline bycatch mitigation measures: conflicts and mutual benefits to elasmobranchs. Fish Fish. doi:10.1111/faf.12143

Godin A, Carlson J, Burgener V (2012) The effect of circle hooks on shark catchability and at-vessel mortality rates in longlines fisheries. Bull Mar Sci 88:469–483

Huang H, Swimmer Y, Bigelow K, Gutierrez A, Foster D (2016) Influence of hook type on catch of commercial and bycatch species in an Atlantic tuna fishery. Mar Policy 65:68–75

ICES (1995) Report from the Study Group on Unaccounted Mortality in Fisheries. *ICES CM* 1995/B:1. International Council for the Exploration of the Sea, Copenhagen

IUCN (2016) The IUCN Red List of Threatened Species. Version 2015-4. International Union for the Conservation of Nature, Gland, Switzerland. http://www.iucnredlist.org/, Accessed 1 April 2016

Kiyota M, Yokota K, Nobetsu T, Minami H, Nakano H (2005) Assessment of mitigation measures to reduce interactions between sea turtles and longline fishery. Proceedings of the 5th SEASTAR2000 Workshop, pp 24–29

Lewison R, Freeman S, Crowder L (2004) Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecol Lett 7:221–225

Lokkeborg S, Bjordal A (1992) Species and size selectivity in longline fishing: a review. Fish Res 13:311–322

Mangel J, Alfaro-Shigueto J, Witt M, Dutton P, Seminoff J, Godley B (2011) Post-capture movements of loggerhead turtles in the southeastern Pacific Ocean assessed by satellite tracking. Mar Ecol Prog Ser 433:261–272

Mejuto J, Garcia-Cortes B, Ramos-cartelle A (2008) Trials using different hook and bait types in the configuration of the surface longline gear used by the Spanish swordfish (*Xiphias gladius*) fishery in the Atlantic Ocean. Collect Vol Sci Pap ICCAT 62:1793–1830

Pacheco R (2013) La pesca con palangre pelágico en el Pacifico panameño. Aspectos operativos de la selectividad de los anzuelos y repercusiones en la captura incidental de tortugas marinas. Master's Degree Thesis. Universidad de Alicante. Departamento de Ciencias del Mar y Biología Aplicada, Alicante, Spain. http://rua.ua.es/dspace/handle/10045/36118. Accessed 11 April 2016

Pacheco J, Kerstetter D, Hazin F, Hazin H, Segundo R, Graves J, Carvalho F, Travassos P (2011) A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. Fish Res 107:39–45

Parga M (2012) Hooks and sea turtles: a veterinary's perspective. Bull Mar Sci 88:731–741

Parga M, Pons M, Andraka S, Rendon L, Mituhasi T, Hall M, Pacheco L, Segura A, Osmond M, Vogel N (2015) Hooking locations in sea turtles incidentally captured by artisanal longline fisheries in the Eastern Pacific Ocean. Fish Res 164:231–237

Piovano S, Balletto E, Di Marco S, Dominici A, Giacoma C, Zannetti A (2004) Loggerhead turtle (*Caretta caretta*) by catches on long-lines: the importance of olfactory stimuli. Ital J Zool 71:213–216

Piovano S, Swimmer Y, Giacoma C (2009) Are circle hooks effective in reducing incidental captures of loggerhead sea turtles in a Mediterranean longline fishery? Aquat Conserv Mar Freshw Ecosyst 19:779–785

Piovano S, Farcomeni A, Giacoma C (2012) Effects of chemicals from longline baits on the biting behaviour of loggerhead sea turtles. Afr J Mar Sci 34:1–5

Ralston S (1990) Size selection of snappers (*Lutjanidae*) by hook and line gear. Can J Fish Aquat Sci 47:696–700

Sales G, Giffoni B, Fiedler F, Azevedo V, Kotas J, Swimmer Y, Bugoni L (2010) Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery. Aquat Conserv: Mar Freshw Ecosyst 20:428–436

Santos M, Coelho R, Fernandez-Carvalho J, Amorim S (2012) Effects of hook and bait on sea turtle catches in an equatorial Atlantic pelagic longline fishery. Bull Mar Sci 88:683–70

Santos M, Coelho R, Fernandez-Carvalho J, Amorim S (2013) Effects of 17/0 circle hooks and bait on sea turtles bycatch in a Southern Atlantic swordfish longline fishery. Aquat Conserv: Mar Freshw Ecosyst 23:732–744

Serafy J, Kerstetter D, Rice P (2009) Can circle hook use benefit billfishes? Fish Fish 10:132–142

Serafy J, Cooke S, Diaz G, Graves J, Hall M, Shivji M, Swimmer Y (2012) Circle hooks in commercial, recreational, and artisanal fisheries: research status and needs for improved conservation and management. Bull Mar Sci 88:371–391

Stokes L, Hataway D, Epperly S, Shah A, Bergmann C, Watson J, Higgins B (2011) Hook ingestion rates in loggerhead sea turtles *Caretta caretta* as a function of animal size, hook size, and bait. Endanger Species Res 14:1–11

Stokes L, Epperly S, MCarthy K (2012) Relationship between hook type and hooking location in sea turtles incidentally captured in the United States Atlantic pelagic longline fishery. Bull Mar Sci 88:703–718

Swimmer Y, Gilman E (eds) (2012) Report of the Sea Turtle Longline Fishery Post-release Mortality Workshop, November 15-16, 2011. NOAA Technical Memorandum NMFS-PIFSC-34. National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu. http://www.pifsc.noaa.gov/library/pubs/tech/NOAA_Tech_Memo_PIFSC_34.pdf. Accessed 1 Oct 2014

Swimmer Y, Empey Campora C, Mcnaughton L, Musyl M, Parga M (2014) Post-release mortality estimates of loggerhead sea turtles (*Caretta caretta*) caught in pelagic longline fisheries based on satellite data and hooking location. Aquat Conserv Mar Freshw Ecosyst 24:498–510

Wallace B, DiMatteo A, Bolten A et al (2011) Global conservation priorities for marine turtles. PLoS One 6:e24510. doi:10.1371/journal.pone.0024510

Wallace B, Kot C, DiMatteo A, Lee T, Crowder L, Lewison R (2013) Impacts of fisheries bycatch on marine turtle populations worldwide: toward conservation and research priorities. Ecosphere 4:40. doi:10.1890/ES12-00388.1

Ward P, Myers R (2007) Bait loss and its potential effects on fishing power in pelagic longline fisheries. Fish Res 86:69–76

Watson J, Epperly S, Foster D, Shah A (2005) Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Can J Fish Aquat Sci 62:965–981

WCPFC and SPC (2016) Workshop on Joint Analysis of Sea Turtle Mitigation Effectiveness. Final Report of the First Workshop 16 March 2016. Western and Central Pacific Fisheries Commission, Pacific Community, Areas Beyond National Jurisdiction Tuna Project: Kolonia, Federated States of Micronesia; Noumea, New Caledona, Rome, Italy

Witzell W (1999) Distribution and relative abundance of sea turtles caught incidentally by the U.S. pelagic longline fleet in the western North Atlantic Ocean, 1992–1995. Fish Bull (Wash DC) 97:200–211

Yokota K, Kiyota M, Okamura H (2009) Effect of bait species and color on sea turtle bycatch in a pelagic longline fishery. Fish Res 97:53–58

Yokota K, Mituhasi T, Minami H, Kiyota M (2012) Perspectives on the morphological elements of circle hooks and their performance in pelagic longline fisheries. Bull Mar Sci 88:623–629