CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/MF21288

MARINE & FRESHWATER RESEARCH

A comparison of catch efficiency and bycatch reduction of tuna pole-and-line fisheries using Japan tuna hook (JT-hook) and circle-shaped hook (C-hook)

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Handling Editor:
Haseeb Randhawa

Received: 5 October 2021
Accepted: 6 January 2022
Published: 22 February 2022

Cite this:
Nguyen KQ *et al.* (2022)
Marine and Freshwater Research
doi:10.1071/MF21288

ABSTRACT

Unwanted bycatch of sea turtles in the tuna fisheries is a global challenge. To evaluate whether the incidental catch of sea turtles could be reduced through changes in fishing gear, this study compared catch rates and bycatch in the tuna pole-and-line with the addition of above-water lights (PL) fisheries using a Japan tuna hook (JT-hook) and a circle-shaped hook (C-hook). There were two phases to this study. First, five PL fishing vessels that used traditional JT-hooks were compared with five PL fishing vessels that used circle-shaped hooks throughout 1 full year of fishing. Results showed that C-hooks significantly reduced bycatch of sea turtle, while negligibly increasing the catch of yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*) tuna. Second, we conducted the onboard research to investigate the effect of JT-hook *v.* C-hook on the catch rates of commercial PL fishery. Results showed that there were higher catch rates of long snouted lancefish (*Alepisaurus ferox*) and wahoo (*Acanthocybium solandri*), but lower catches of thresher shark (*Alopias* spp.) on C-hooks, with no significant differences for other species considered. Our results suggest that the use of C-hooks in the PL fishery is beneficial to protected endangered sea turtle species.

Keywords: bycatch mitigation, circle hooks, conservation, ecological benefit, handlines, hook effect, sea turtle, tuna fishery, Vietnamese fisheries.

Introduction

Sea turtles are recognised as endangered species throughout tropical and temperate regions of the world's oceans and threatened by ongoing bycatch effects in long-line fisheries. Six of the seven extant species of sea turtles have been assessed for the IUCN Red List of Threatened Species (see https://www.iucnredlist.org/search?query=Sea%20turtle&searchType=species), and international trade and commercial fishing of these species is prohibited (CITES 2021). The seventh species is listed as data deficient. Sea turtles are protected by the United States *Endangered Species Act* (Gilman *et al.* 2007) and similar laws of other nations including Vietnam (Nguyen 2008). Because sea turtles are highly migratory species (Swimmer and Brill 2006), which easily interact with pelagic longlines fisheries (Food and Agriculture Organization of the United Nations 2001), an estimated 200 000 loggerheads (*Caretta caretta*) and 50 000 leatherbacks (*Dermochelys coriacea*) were therefore annually caught by pelagic longlines globally (Lewison *et al.* 2004). There is a growing body of research to show that changes in fishing methods and gear can reduce sea turtle catch rates and injury, such as restricted annual fishing effort, limited soak time, mandatory fishing depth (i.e. longlines mandate to set at deeper turtles' preferred depth), and adjusting fishing season (Swimmer and Brill 2006; Gilman and Huang 2017; Swimmer *et al.* 2020).

In Vietnam, all species of sea turtles are listed as endangered and it is prohibited to catch or collect sea turtles or their eggs (Ta 2006; Nguyen 2008); However, they are incidentally captured by different fishing methods (Do *et al.* 2019). To our knowledge, very little information on bycatch of sea turtles in the Vietnamese fisheries has been documented. The only piece of incidental information came from studies by Vu and Nguyen (2011), Do *et al.* (2019), and Vietnam Tuna Association (2020) during the evaluation of the catch composition of longline fisheries. The reports showed numbers of sea turtles incidentally caught by JT-hook throughout the pelagic longlines and pole-and-line fisheries.

Post-release mortality is likely to be high among sea turtles caught by pelagic longlines using JT or J-hooks (Chaloupka *et al.* 2004*a*; Watson *et al.* 2005; Swimmer *et al.* 2014). The relative degree of impact on post-release mortality as a function of hook location and amount of gear remaining at release (Chaloupka *et al.* 2004*a*; Watson *et al.* 2005). Deep hooking, releasing entangled sea turtles, and resuscitation of drowned animals are associated with the highest mortality rates (Chaloupka *et al.* 2004*a*), which would die within 90 days of release because of serious injuries caused by hooks or line entanglement following release (Watson *et al.* 2005). Additionally, a substantial number of sea turtles die because of hunger as a result of an existing hook (Jordan *et al.* 2013).

Vietnamese law requires fishermen to release incidentally captured sea turtles, which is accomplished by cutting the fishing line because it is quick or because the hook is deep in the throat and difficult to remove (Vietnam Tuna Association 2020). Fishing in ways that minimise capture of non-target species from the catch is the best approach to maintaining healthy fish communities and to minimise negative effects on endangered species (Gilman and Huang 2017). Studies have demonstrated the conservation benefits of the circle-shaped hook (C-hook) for a variety of fisheries, without significant reductions in targeted species (Kerstetter and Graves 2006; Sales *et al.* 2010; Pacheco *et al.* 2011; Rudershausen *et al.* 2012; Huang *et al.* 2016; Swimmer *et al.* 2017; Burns 2019).

Tuna is a commercially important species on the central coast of Vietnam, in particular the provinces of Khanh Hoa, Phu Yen and Binh Dinh. Commercial harvesting of tuna contributes substantially to the likelihood for coastal communities and regional economic development in terms of foreign income earnings (Nguyen and Gao 2010; Nguyen and Jolly 2018). In 2019, the export of tuna in Vietnam amounted to US$720 million, accounting for 13.3% of the country's marine fisheries export value (Vietnam Association of Seafood Exporters and Producers 2020), and the export value of this fishery is expected to increase (Nguyen and Jolly 2018). Historically, the fishery began in 1992 under a Japan International Cooperation Agency project which included technology transfer and provision of pelagic longline vessels targeting yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*; Duong 2002; Nguyen *et al.* 2013). Until 2011, tuna was harvested only by using pelagic longline gear. Fishermen used a 20–30-km longline including 800–1200 hooks baited with frozen squid (*Sthenoteuthis oualaniensis*) or yellowfin flyingfish (*Cypselurus poecilopterus*) and soaked overnight at the depth between 80 and 100 m (Nguyen 2011). Starting in 2011, fishers transitioned to using pole-and-line with the addition of above-water lights (PL) that were installed along the vessel's cabin, which increased catch rates (Nguyen and Tran 2014; Tran 2014, 2015). This PL fishing method has replaced the traditional tuna longline fishery in the waters of Vietnam (Nguyen and Tran 2014; Tran 2014, 2015). Different types and sizes of hooks are used in the PL fishery, but the 3.8 sun Japan Tuna (JT)-hook is most commonly used (Tran 2015; Do *et al.* 2019, Vietnam Tuna Association 2020). Tuna fishers are reluctant to change fishing methods because even a small reduction in target catches could have a significant economic impact.

The objective of the present study was to compare the catch rates of target and incidental catch species of sea turtle, incorporating temporal and spatial conditions in a commercial experimental tuna HL fishery comparing C-hooks against traditional JT hooks, operating in the Exclusive Economic Zone of Vietnam. The study was conducted in two phases including the dockside data collection and field conditions. The research location was specifically chosen on the basis of where there is a high number of tuna fishing vessels in Vietnam. Conservation benefits through fishery improvements are increasingly being used to improve market conditions through certifications, which also improves market prices. Improved economic value can be realised by demonstrating strong fishery management. For the Vietnamese tuna fishery to transition from JT-hooks to C-hooks, clear evidence showing improved or equivalent catch rates is needed, in addition to conservation benefits for endangered sea turtle species.

Materials and methods

Dockside data collection

This study collected commercial fishing data from 10 tuna PL fishing vessels landing in Nha Trang city, Vietnam, from January to December 2020. These vessels were members of a fishing cooperative that operated on the same fishing grounds within ~200 nautical miles (~370 km) from the Hon Ro fishing port. Five vessels used the traditional 3.8 sun JT-hooks (manufactured by Hoc Huong located in Hoai Huong, Hoai Nhon, Binh Dinh, Vietnam), defined as the control vessels, and five fishing vessels were equipped with the C-hooks (Code 3493-0014) size 14/0 (manufactured by Dong Ah Fishing Industries Co., Ltd, Busan, South Korea, see http://www.hi-fishing.com), defined as the experimental vessels. Both hook types were made of stainless steel and had a 0° offset (Fig. 1). The capacity of the control and experimental vessels was identical, including such as length overall (LOA), main engine and light power (Table 1). Vessels ranged between 15.3 and 17.4 m long and were equipped

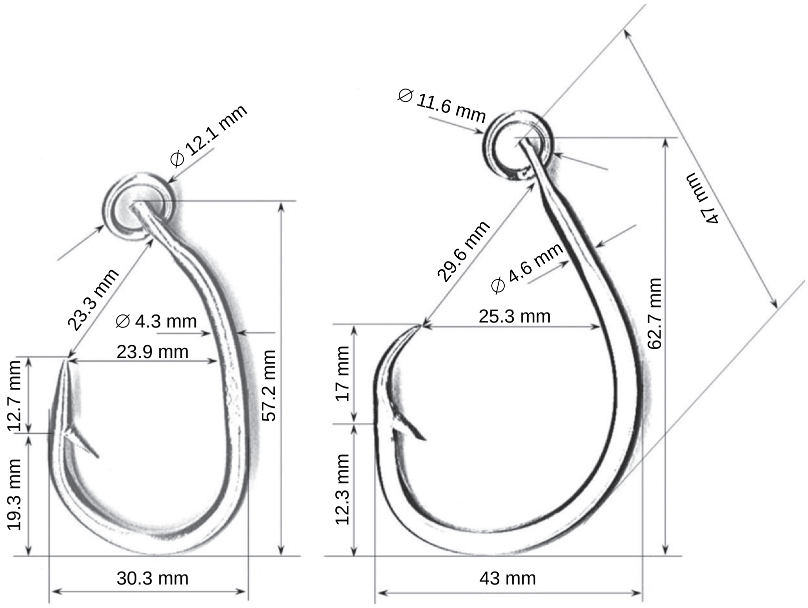


Fig. 1. A 3.8 sun JT-hook (left panel) and C-hook, size 14, Code 3493-0014 (right panel) and its dimensions used in this study. JT-hooks were manufactured by Hoc Huong (Hoai Huong, Hoai Nhon, Binh Dinh, Vietnam), and C-hooks were imported from Dong Ah Fishing Industries Co., Ltd, Busan, South Korea (see http://www.hi-fishing.com). Both JT-hooks and C-hooks had 0° offset. Ø, diameter.

with a 19–32-kW light (Table 1). Each vessel used four fishing rods (see details of construction and specifications of fishing gear in *Onboard research* section). Commercial fishing was commonly conducted during the third-, new and first-quarter moon phases, whereas no fishing was conducted during the full moon (i.e. from 11th to 19th of the lunar month) to avoid low catch rates (Nguyen *et al.* 2013).

When the vessels unloaded fish, the number of yellowfin and bigeye tunas caught by each vessel was recorded. Although the PL also caught incidental species (retained for commercial purpose) such as thresher shark (*Alopias*), long snouted lancetfish (*Alepisaurus ferox*), swordfish (*Xiphias gladius*), and wahoo (*Acanthocybium solandri*), those bycatch species were not recorded, and are excluded from our catch comparison analysis. Data on bycatch of sea turtles incidentally caught and released during each trip were extracted from the official fishing logbook, which were considered to be accurately maintained and a good representation of turtle bycatch. Captains of the fishing vessels involved this study were requested to record additional information on hook position (mouth edge or throat), and release method (hook removed or line cut) on every trip because sea turtles are required to be released at sea (Nguyen 2008). Other information such as date of departure and return, and the number of fishing nights was also recorded. Catch and fishing operation of the vessels are summarised in Table 1.

Onboard research

The field experiment was conducted by scientific observers aboard the 15.2 m LOA commercial tuna fishing vessel *KH 96281TS* that fished in the South China Sea, ~120 nautical miles (~222 km) south-west of the Spratly Islands (Fig. 2), from 5 January to 18 April 2021. The vessel was equipped with 20-kW metal halide lights and 2-kW fluorescent tube lights, which were similarly located on the starboard and port sides of the vessel. The fishing gear used for the tuna PL fishing experiment is shown in Fig. 3, and is typical of those used in Vietnam. There were two hooks placed at 60- and 80-m depth on a line (Fig. 3). Four bamboo fishing rods (~4 m long) were installed in fixed holders at the stern, bow, and either side of the vessel, at angles of 100–120°. A 10-mm-diameter ring was attached on the end of the rod, allowing the monofilament mainline (2.2 mm in diameter) to smoothly slide. Two monofilament branch lines, 4 m long, 1.8 mm in diameter, were attached at intervals of 20 m and then a 3-kg weight was fixed to the end of the main line (see Fig. 3 for details). On the *KH 96281TS*, there were four fishing rods, with two rods on each side of the vessel. Live squid (*Sthenoteuthis oualaniensis*) was used as bait. Squid were tethered through the stabilising fin with the fishing hook, so as to keep the bait alive and to better attract tuna. Experimental fishing was undertaken using two rods with C-hooks in the port side and two rods with JT-hooks in the starboard side. So as to reduce any potential experimental bias, the hook types were switched to alternating sides of the vessel every night.

Fishing operations were conducted during the night only, from sunset to dawn (from 1800 to 0600 hours), drifting ~5 nautical miles (~9 km) each night with a sea anchor in place, while the fishing lamps were turned on to attract fish. The PL was regularly checked every 30 min, to ensure that the bait was intact and that the fishing line was functioning. When a fish was hooked, all crew worked to retrieve the fishing line manually. The hauling process took from 2 to 4 min depending on how fish was struggling. When tuna were caught, they were immediately sacrificed, processed and cooled to maintain quality. However, when a sea turtle was caught, it was

Table 1. Summary details for the hook type comparison from the 10 pole-and-line fishing vessels that were used for fishing between January and December 2020.

Vessel	Hook type	Length overall (m)	Engine (HP)	Lightpower (kW)	Total trip	Total fishing nights	Trip duration (range)	Number of fishing nights per trip (range)	Total catch in number		Total number of turtles
									Bigeye	Yellowfin	
KH 91568TS	C	15.4	440	19	11	177	20 (19–23) days	16 (14–18) days	57	512	1
KH 96614TS	C	16.7	450	25	12	194	20 (18–23) days	16 (15–18) days	49	556	2
KH 94338TS	C	16.7	466	32	10	157	20 (18–21) days	16 (14–17) days	45	583	3
KH 96586TS	C	15.7	410	30	11	174	20 (19–22) days	16 (14–18) days	44	685	2
KH 91927TS	C	16.8	350	32	12	191	20 (18–22) days	16 (14–17) days	46	702	2
KH 91189TS	J	17.4	410	20	12	188	20 (18–22) days	16 (15–18) days	38	531	3
KH 95445TS	J	15.3	360	26	12	186	19 (18–21) days	16 (14–17) days	53	540	6
KH 96176TS	J	15.6	510	25	10	165	21 (19–22) days	17 (15–18) days	39	513	5
KH 92486TS	J	16.5	410	32	11	178	20 (18–22) days	17 (15–18) days	44	667	8
KH 95185TS	J	16.4	350	32	11	178	20 (19–23) days	16 (15–19) days	49	613	7

quickly retrieved alive using a landing net, the hook was removed and the turtle was released within 1 min.

All yellowfin and bigeye tunas were counted, measured (total length to the nearest centimetre), and weighed (wet weight including gills and viscera) to the nearest 0.1 kg. The depth of fish hooks was also noted. For experimental fishing, all other non-target species also were counted and recorded, but not measured and weighed. If a sea turtle was hooked, it was recorded, classified by species, and the hook position was noted before it was returned to the ocean.

Statistical analysis

For dock site data, Generalised Additive Mixed Models (GAMMs) were used to compare the catch between the vessels using the JT-hooks and those that used C-hooks, where the catch was calculated as the number of individuals caught per monthly trip for each vessel. Fishing effort was defined as the time in hour that the fishing vessel actually fished in a monthly trip. GAMMs employ a class of equations called smoothers, which are algorithms that attempt to generalise data into smooth curves by local fitting to subsections of the data (Beck and Jackman 1998). We assessed the variation of catch, while including potentially confounding time series and vessel characteristic variables. The model for the catch was as follows:

$$\begin{aligned}\log(catch) = {} & \alpha + hooktype + s(month) \\ & + s(fishingday) + s(vessellength) \\ & + s(vesselpower) + s(lightpower) \\ & + (1|vessel) + offset(\log(effort)) + \varepsilon \quad (1)\end{aligned}$$

where *catch* as defined above is a function of variables that included the linear term of *hooktype* (C-hook *v.* JT-hook), and smooth terms for *month* (1–12), the number of fishing days per trip – *fishingday* (14–19 days), vessel capacity, i.e. *vessellength* (15.3–17.4 m), engine power – *vesselpower* (350–510 HP) and *lightpower* (19–32 kW); α is the intercept; s is a thin-plate smoothing-spline function; and ε is an error term. Different smoothing functions were applied for the dependent variables in the models. Because of the potential non-linear relationships of catch with month, a cyclic cubic regression spline that forces the response to have the same start and endpoint was handled to smooth the month predictor. The other predictor used was a thin-plate smoothing spline with an automatic penalising function that can zero a term completely, i.e. exclude the effect of the independent variable from the model. The vessel ID was treated as a random effect to account for inter-annual differences and accommodate repeated-measurements. Fishing effort was used as an offset. To avoid over-fitting the models and to obtain spatially relevant responses (Lehmann *et al.* 2002; Sandman *et al.* 2008), the maximum number of knots for each of the smoothers was limited to four ($k = 4$), allowing

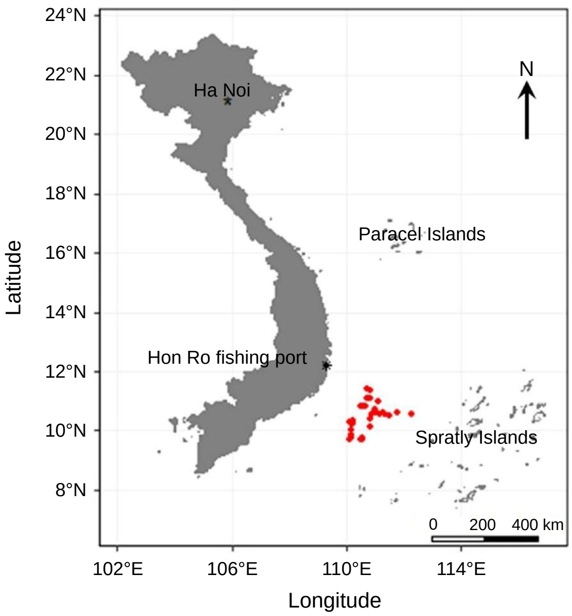


Fig. 2. Map of the area where we conducted the onboard research from January to April 2021, showing all locations fished (red points).

the smoother to divide the response from each explanatory variable into a maximum of three parts. We tested and found that the best model fit was produced using a Poisson error structure with a link-log. Models were visually inspected for spatial autocorrelation by plotting smoothed correlograms of model residuals (Bjørnstad and Falck 2001). The models were run separately for sea turtles, yellowfin tuna and bigeye tuna, as well as pooled data for yellowfin and bigeye tunas. The GAMMs were performed in *gamm4* package in R (ver. 0.2-6, S. Wood and F. Scheipl, see https://cran.r-project.org/web/packages/gamm4/).

The Generalised Additive Models (GAMs) were applied to explain the variability in catch for target and bycatch (byproduct) species during the onboard research during January (1), March (3) and April (4). February was not sampled because of a break of the Lunar New Year. In this analysis, moonphase was a continuous variable and varied between 0 for new moon and 1 for full moon. Definition of moonlight for each fishing night was estimated with the *lunar* package in R (ver. 0.1-04, E. Lazaridis, see https://cran.r-project.org/web/packages/lunar/). We incorporated this continuous variable because catch, as a factor in our analysis, was known to be influenced by lunar rhythm and natural light, typical for most pelagic fisheries (Afonso *et al.* 2021; Nguyen *et al.* 2021). For these analyses, the catch for each species was standardised as the number of fish caught in the hook for nightly catch. Depth was the category variable (60 and 80 m). The candidate model was as follows:

$$\log(catch) = \alpha + hooktype + depth + s(month) + s(moonlight) + \varepsilon \quad (2)$$

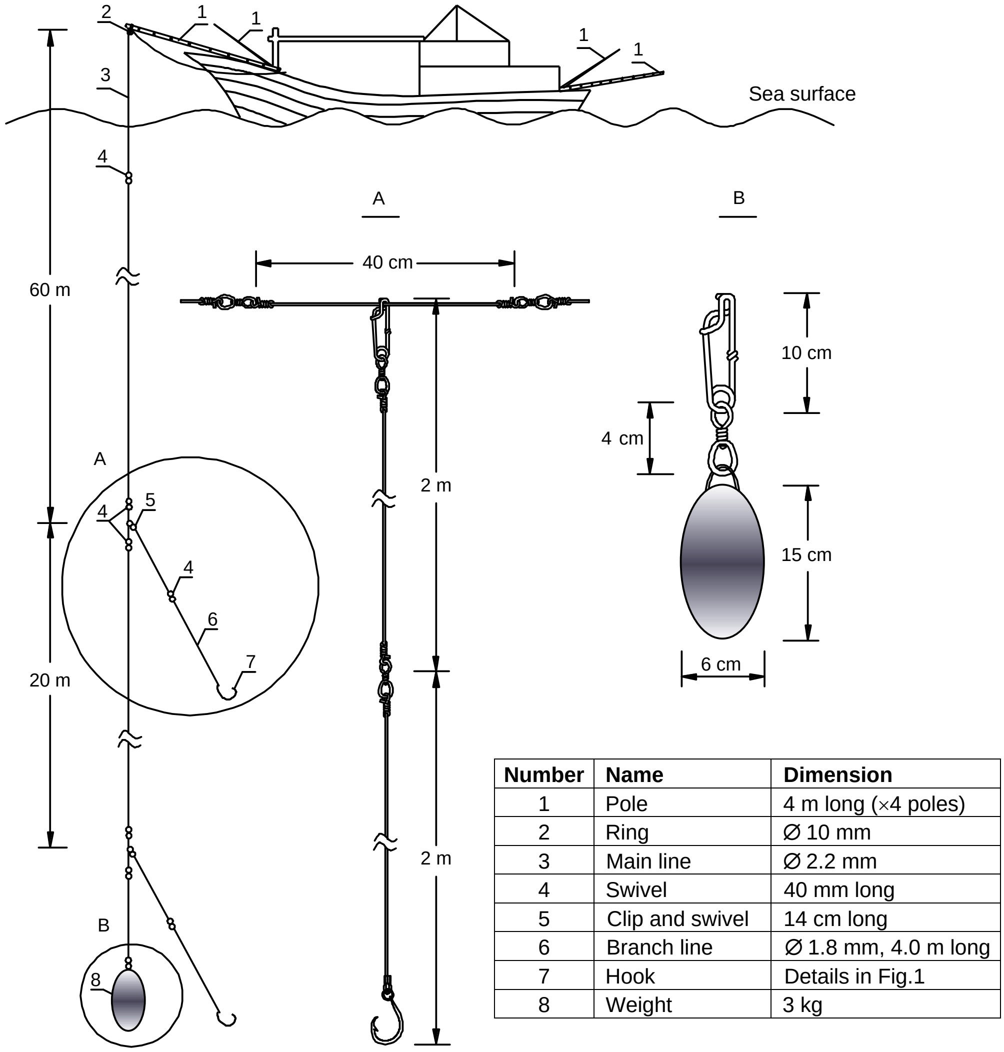
where α is the intercept; s is a thin-plate smoothing-spline function; and ε is an error term as defined above. The same fishing effort was applied during the onboard research (i.e. same fishing day, number of rods and hooks); thus, fishing effort was not included in the model as an offset. Analyses were conducted separately for each species.

For statistical analyses using GAMMs, the deviance and the statistical significance of the explanatory variables are determined on the basis of a backward stepwise model-selection procedure based on a generalised cross-validation (GCV) used to build a final model. For the dockside data, the full model including *hooktype*, *month*, *fishingday*, *vessellength*, *vesselpower* and *lightpower* variables was tested (Eqn 1). We then conducted stepwise model simplification, dropping non-significant terms one at a time until all terms in the model were statistically significant at a 5% level (Crawley 2007). This procedure was repeated for GAMs for the onboard research data, which included *hooktype*, *depth*, *month* and *moonphase* in the initial model (Eqn 2). In cases where all variables were equally significant, different combinations of explanatory variables were tested, and the combination with the lowest GCV score, highest deviance explained, and minimum Akaike information criterion with a correction for small sample sizes (AICc), using the funtion *AICc* from the *AICcmodavg* package (ver. 2.3-1, M. J. Mazerolle, see https://cran.r-project.org/web/packages/AICcmodavg/index.html), was chosen as the final model. The effect of the predictors in the final models was evaluated by partial response curves to visually represent the relationship between the response and the explanatory variables. The QQ-plot of the deviance residuals, deviance residuals *v*. linear plots, and deviance residuals *v*. fitted plot for all species show that the applied models were well fitted with our data for both dockside (Supplementary Fig. S1) and onboard (Supplementary Fig. S2) research. Here, the deviance residuals showed a random distribution, and thus, met the assumption of linearity. In addition, statistical model showed that the variance of the residuals was equal and therefore the assumption of homoscedasticity was met and had an appropriateness of the fitted model in the residual *v*. fitted values.

For onboard research, the analysis of catch proportion for yellowfin and bigeye tuna caught by C-hooks and JT-hooks at each length class was performed using the Generalised Linear Mixed-effect Model (GLMM), with catch proportion as a dependent variable, length class as the independent variable (fixed effect), and trip number as a random effect, following the method of Holst and Revill (2009). The catch proportion was calculated by

$$N_{\mathrm{Lexp}} \div (N_{\mathrm{Lexp}} + N_{\mathrm{Lctr}})$$

where N_{Lexp} is the number of fish of length L caught by the C-hook and N_{Lctr} is the number of fish of length L caught by the JT-hook. In this procedure, a polynomial GLMM was



Number	Name	Dimension
1	Pole	4 m long (×4 poles)
2	Ring	Ø 10 mm
3	Main line	Ø 2.2 mm
4	Swivel	40 mm long
5	Clip and swivel	14 cm long
6	Branch line	Ø 1.8 mm, 4.0 m long
7	Hook	Details in Fig.1
8	Weight	3 kg

Fig. 3. Schematic drawing of a tuna pole-and-line used in this study. The gear is not drawn to scale. Ø, diameter.

used to fit curves for the expected proportions of catch length by using the *glmer* function of the *lme4* package. We began by using lower-order polynomials, i.e. constant, linear, quadratic and cubic, to fit the proportions at each length class retained in the C-hook to those retained by C-hook and JT-hook, followed by subsequent reductions until all terms showed a significance ($P < 0.05$) on the basis of Wald's test, with removal of one term at each step to determine the best-fit model. The best-fit model was chosen on the basis of the minimum AICc by using the function *AICctab* from the *bblme* package (ver. 1.0.23.1, B. Bolker, see https://cran.r-project.org/web/packages/bbmle/index.html). The data were modelled with a binomial distribution. In this analysis, there is no difference in catch rates between C-hook and JT-hook at given lengths if the catch proportion equals 0.5, whereas a proportion greater than 0.5 indicates that more fish were captured by C-hooks, and *vice versa* (Holst and Revill 2009; Nguyen *et al.* 2020; Tran *et al.* 2020). For example, if the proportion was 0.75, 75% of fish at a given length class was caught by the C-hook and 25% by the JT-hook. The confidence intervals (CIs) indicate the significance level between treatments; if the CIs overlap by 0.5, there is then no statistically significant difference in catch-at-length between C-hooks and JT-hooks at the given length class.

Results

Dockside data analysis

Bycatch comparison for sea turtle

In total, 39 sea turtles were captured during the Phase 1 of the study, including 10 caught in C-hooks and 29 caught in JT-hooks (Table 1). By species, there were 28 loggerhead (*Caretta caretta*), 6 green turtle (*Chelonia mydas*) and 5 olive ridley turtle (*Lepidochelys olivacea*). Individuals caught with JT-hooks hooked in either the throat (n = 20) or in the mouth (n = 9), whereas C-hooks caught all turtles in the corner of the jaw. All sea turtle species were released alive following removal of the attached fishing gear (n = 20) or cutting the branch line as close to the animal as safely possible (n = 19). Sea turtles caught by C-hooks and JT-hooks that could not remove the attached gear were 2 and 17 respectively.

We performed different models to identify the best-fit model on the basis of the model selection criteria. The best model for sea turtles included the light power predictor (Supplementary Table S1). The GAMMs indicated that C-hooks produced a statistically significant reduction in the catch of sea turtles (Table 2). The modelled catch was 0.18 (95% CI: 0.1–0.3) for C-hooks and 0.52 (95% CI: 0.3–1.8) for JT-hooks. Model predictions indicated that the catch of sea turtle increased with light power (Table 3, Fig. 4). There was no statistical difference in catch of sea turtles among months. The deviance explained by the model for sea turtle was 22.4%, indicating the majority of variation in catch of sea turtles could not be explained by the GAMMs model.

Catch comparison for target species

In total, 112 fishing trips were undertaken with 1788 fishing nights, and 6366 tunas were caught (Table 1). A fishing trip varied between 18 and 23 days, fishing 14–19 nightly catches per trip and catching 31–90 fish (27–86 yellowfin and 0–8 bigeye tuna) per trip. Yellowfin tuna dominated the catch for both control and experimental vessels, accounting for 92.7% of the catch, although bigeye tuna were also caught (Table 1).

The comparison showed that hook type had no effect on the catch of yellowfin tuna, although the experimental vessels using the C-hook had a slightly higher catch rate than did the control vessels, which was not statistically significant (Table 2). The modelled catches for yellowfin tuna were 54 (95% CI: 48.5–60.2) and 51 (95% CI: 47.7–59.1) fish per vessel per trip for C-hooks and J-hooks respectively. For bigeye tuna, the catch rate was also not significantly different between the control and experimental vessels. The modelled catch for bigeye tuna was 4.3 (95% CI: 3.8–4.9) for the experimental vessel and 4.0 (95% CI: 3–5.4) for the control vessel. For all species combined, our statistical model showled that the experimental vessels captured 58.4 (95% CI: 53.6–65.2) individuals per trip, which was slightly more than that for the control vessel, which caught 55.1 (95% CI: 52.8–64.1) individuals per trip; however, the difference was not statistically significant.

Model selection showed that the fit model for yellowfin tuna and as well as yellowfin and bigeye tuna combined included month and light power (Supplementary Table S1). The GAMMs analysis showed that the variations in the catch rate for yellowfin tuna could be explained mainly by changes in light power and month (Table 3). The vessel length, engine and number of fishing nights did not contribute to differences among the tested models. The partial effects of the predictors in each model are shown in Fig. 4. The catch rate of yellowfin tuna increased with the light power (Fig. 4). In addition, the model showed that the catches differed among months, with the highest catch rate in April and May, and the lowest catch in October (Fig. 4). For bigeye tuna, predictors included in the model did not affect the catch rate (Table 3). For all species combined, light power and month were also significant predictors (Table 3). The catch also increased with the light power (Fig. 4). The model showed a temporal variation, with peaks of catch rate in May and the lowest catch in October (Fig. 4). The deviances explained by the models for yellowfin and bigeye tuna, and pooled data were 43.2, 36.6 and 44.2% respectively (Table 3).

Onboard data analysis

Catch comparison

In total, three experimental trips with 43 fishing nights were conducted during onboard research. Both C-hooks and

Table 2. Parameter estimates, fit statistics, and variation from the random effect of GAMMs for tuna and sea turtle comparison, by using vessel ID as a random factor, represented in Eqn 1.

Species	Parameter	Estimate	s.e.	z-value	*P*
Sea turtle	Intercept	−1.72	0.32	−5.45	<0.001
	J-hook	1.06	0.37	2.90	0.004
Yellowfin tuna	Intercept	3.99	0.06	72.43	<0.001
	J-hook	−0.06	0.08	−0.73	0.466
Bigeye tuna	Intercept	1.46	0.06	20.33	<0.001
	J-hook	−0.08	0.09	−0.86	0.390
Yellowfin and bigeye combined	Intercept	4.08	0.05	82.13	<0.001
	J-hook	−0.07	0.07	−1.02	0.308

The model was run separately for yellowfin tuna, bigeye tuna, both species combined, and sea turtle. s.e., standard error of the estimate.

Table 3. The effect of time series and vessel characteristics, by using GAMMs, on the catch of yellowfin tuna, bigeye tuna, both species combined, and sea turtle, represented in Eqn 1.

Species	*n*	GCV	Deviance explained (%)	AICc	Predictor	d.f.$_e$	d.f.	χ^2	*P*
Sea turtle	112	0.2	22.4	160.5	Light power	0.73	3.00	2.38	0.07
Yellowfin tuna	112	98.4	43.2	838.8	Light power	1.35	3.00	34.49	<0.001
					Month	2.86	3.00	32.14	<0.001
Bigeye tuna	112	4.3	36.6	484.7	n.a.	n.a.	n.a.	n.a.	n.a.
Yellowfin and bigeye combined	112	110.1	44.2	847.7	Light power	1.41	3.00	34.86	<0.001
					Month	2.81	3.00	27.30	<0.001

n.a., not applicable, where predictors did not have an effect on the CPUE.

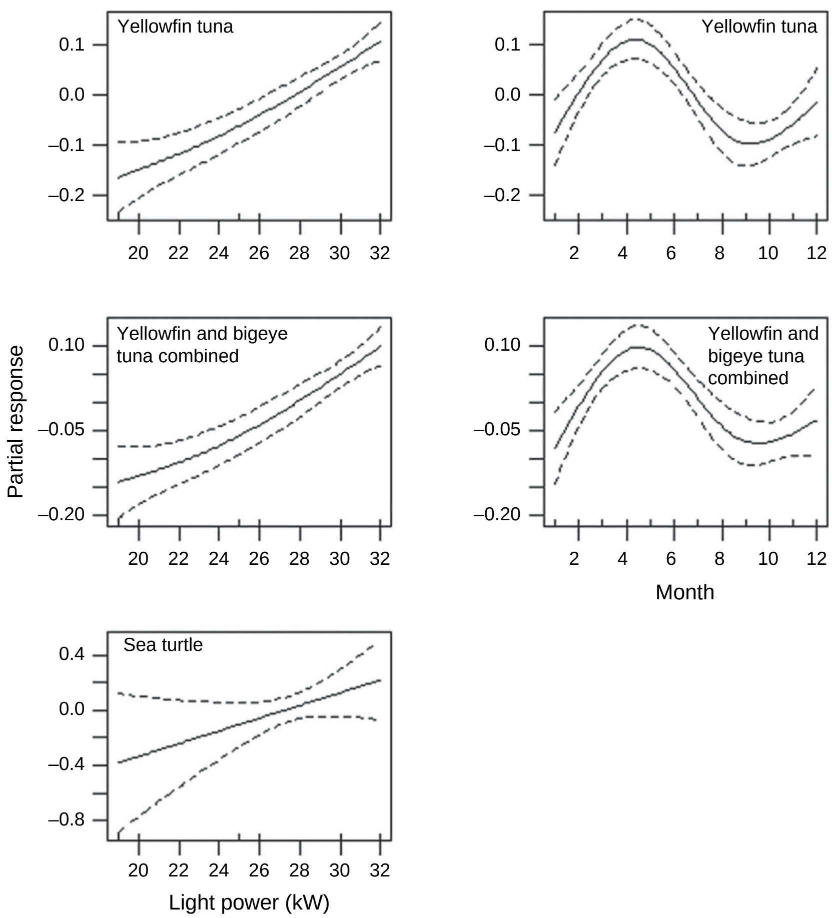


Fig. 4. Partial response curves obtained from the GAMMs for catch of yellowfin tuna, yellowfin and bigeye tuna combined, and sea turtle sampled in the dockside, in relation to time series and vessel characteristics. All graphs show the partial effects of each significant predictor on the catch. Values above 0 indicate a positive effect of the predictor on the catch.

JT-hooks captured the same 14 fish species, consisting of 1059 individuals (571 for C-hooks and 488 for JT-hooks), including the two target tuna species yellowfin and bigeye (Table 4). The JT-hooks captured two sea turtles (olive ridley and loggerhead), which included an individual hooked in the throat and other hooked in the mouth, whereas none were caught on C-hooks (Table 4). Yellowfin tuna, long snouted lancetfish, wahoo, thresher shark and swordfish dominated the catch. Together these five species comprised 82.31 and 76.02% of the total catch of all species captured by the C-hooks and JT-hooks respectively (Table 4), and only these five species, along with bigeye tuna which was a targeted species, were included in our analysis.

The catch composition was not significantly different between the different types of hook, except for the long snouted lancetfish and wahoo, which showed a significantly higher catch rate with the C-hook than the JT-hook, and for the thresher shark, which showed an opposite pattern of a significantly higher catch rate with the JT-hook (Table 5). Modelled catch rates for yellowfin tuna, bigeye tuna, long snouted lancetfish, wahoo, thresher shark and swordfish for the C-hooks were 1.11, 0.14, 2.28, 2.47, 0.19 and 0.6

Table 4. Summary of onboard research including the number of species caught by different hook types and trips.

Species	Scientific name	Trip 1 (5–19 January)		Trip 2 (5–19 March)		Trip 3 (4–18 April)		Total		Percentage of total catch	
		C-hooks	JT-hooks	C-hooks	JT-hooks	C-hooks	JT-hooks	C-hooks	JT-hooks	C-hooks	JT-hooks
Target species (retained)											
Yellowfin tuna		23	29	30	24	36	32	89	85	15.59	17.42
Bigeye tuna		4	1	6	2	3	4	13	7	2.28	1.43
Bycatch species (retained)											
Long snouted lancetfish	*Alepisaurus ferox*	65	36	68	48	55	44	188	128	32.92	26.23
Wahoo	*Acanthocybium solandri*	32	28	46	25	32	15	110	68	19.26	13.93
Thresher shark	*Alopias* spp	15	12	10	21	13	26	38	59	6.65	12.09
Swordfish	*Xiphias gladius*	10	16	22	10	13	5	45	31	7.88	6.35
Sailfish	*Istiophorus platypterus*	6	8	7	5	9	14	22	27	3.85	5.53
Escolar	*Lepidocybium flavobrunneum*	6	6	5	4	5	5	16	15	2.80	3.07
Great barracuda	*Sphyraena barracuda*	5	6	4	4	5	6	14	16	2.45	3.28
Mahi mahi	*Coryphaena hippurus*	3	5	3	5	6	6	12	16	2.10	3.28
Oil-fish	*Ruvettus pretious*	4	2	3	6	6	7	13	15	2.28	3.07
Blue shark	*Prionace glauca*	2	5	1	2	1	4	4	11	0.70	2.25
Blue marlin	*Makaira nigricans*	1	3	2	2	0	1	3	6	0.53	1.23
Black marlin	*Istiompax indica*	1	1	2	1	1	0	4	2	0.70	0.41
Bycatch (released)											
Olive ridley	*Lepidochelys olivacea*	0	0	0	1	0	0	0	1	0.00	0.20
Loggerhead	*Caretta caretta*	0	0	0	0	0	1	0	1	0.00	0.20

Table 5. Parameter estimates, fit statistics and variation from the GAM models for catch comparison, represented in Eqn 2.

Species	Parameter	Estimate	s.e.	z-value	*P*
Yellowfin tuna	Intercept	0.11	0.24	0.45	0.657
	J-hooks	−0.25	0.07	−3.57	0.358
	Depth	0.00	0.00	−0.92	0.358
Bigeye tuna	Intercept	−1.94	1.59	−1.22	0.224
	J-hooks	−0.62	0.47	−1.32	0.187
	Depth	<0.001	0.02	0.00	1.000
Long snouted lancetfish	Intercept	0.83	0.40	2.06	0.039
	J-hooks	−0.38	0.11	−3.36	0.001
	Depth	0.00	0.01	−0.23	0.822
Wahoo	Intercept	0.91	0.53	1.71	0.087
	J-hooks	−0.48	0.15	−3.12	0.002
	Depth	−0.01	0.01	−1.35	0.178
Thresher shark	Intercept	−1.67	0.74	−2.24	0.025
	J-hooks	0.44	0.21	2.12	0.034
	Depth	0.01	0.01	1.11	0.265
Swordfish	Intercept	−0.51	0.81	−0.63	0.532
	J-hooks	−0.37	0.23	−1.60	0.110
	Depth	<0.001	0.01	−0.23	0.819

The model was run separately for each species. s.e., standard error of the estimate.

individuals per hook per night respectively, compared with 0.87, 0.08, 1.55, 1.53, 0.29 and 0.41 individuals per hook per night for those species caught on JT-hooks respectively (Table 5). Although there were no significant differences in the catch rate between 60- and 80-m depths for all species (Table 5), the comparison showed that the total catches were markedly more variable over the day of lunar month (Fig. 5).

The backward stepwise model selection procedure (Supplementary Table S2) and the decrease of residual deviance indicated that the catch rates for yellowfin tuna, long snouted lancetfish, and thresher shark were significantly dependent on the moonphase (Table 6), with higher catch rates observed during the low moonlight density. In other words, catch rates significantly decreased with the high lunar illumination levels (Fig. 6). The moonphase did not contribute to the tested models for bigeye tuna, wahoo and swordfish. In addition, there were no differences in catch rate for all species among January, March and April. The deviance explained by the models was low for all species, ranging from 4 to 13.4% (Table 6).

Body length comparison

The total length of yellowfin tuna caught by the C-hooks ranged from 100 to 172 mm, corresponding with the weight of 17–86 kg, compared with those caught by JT-hooks ranging from 90 to 165 cm and weighing between 16 and 70 kg (Fig. 7). The total length of bigeye tuna ranged from 80 to 173 cm and the weight from 16 to 103 kg for the different treatments (range = 103–167 cm and 22–98 kg for C-hooks, and 80–173 cm and 16–98 kg for JT-hooks; Fig. 7).

For yellowfin tuna, a first-order polynomial (linear) GLMM was the best fit for the length class comparison, having the lowest AICc value and all model parameters being statistically significant (Table 7). The model showed that C-hooks are more likely to catch larger yellowfin tuna than are JT-hooks (Fig. 7). The significant differences in catch-at-length between hook types were shown where CIs did not overlap the 0.5 band. By contrast, there was no difference in size-based selectivity between the treatments for the moderate-sized animals based on the 0.5 overlap in the CI (Fig. 7).

A GLMM model with a logit-quadratic curve best fit the proportion of bigeye tuna at each length class on the basis of the lowest AICc value and all model parameters being statistically significant (Table 7). There were no statistically significant differences in catch rate or size-based selectivity between the experimental treatments for bigeye tuna; similar variation was observed for both C-hook and JT-hook caught fish (Fig. 7).

Discussion

The use of C-hooks in the Vietnamese tuna PL fishery significantly reduced incidental catch of protected sea turtle species, and also maintained commercial catch rates for targeted species. Results indicated that using C-hooks reduced the proportion of sea turtles that swallow the hook, as compared to swallowing the hook in the mouth. This potentially improves the post-release mortality rate and has the ecological benefit (Chaloupka *et al.* 2004*a*; Swimmer *et al.* 2014; Gilman and Huang 2017). Using C-hooks would benefit existing conservation efforts to protect sea turtle species in the South China Sea, and tuna harvesters can maintain their economic benefit. This study has added further evidence that C-hooks should be recommended as an alternative to the traditional JT-hook in mitigating threatened species such as loggerhead, green and olive ridley turtles in the PL fishery.

Our study showed that the PL fishing vessel captured an average of 0.52 (±0.37 s.e.) and 0.18 (±0.32 s.e.) individual sea turtles per monthly trip for vessels that used JT-hooks and C-hooks respectively, which were released alive following removal of the attached fishing gear. This catch rate was less than that reported for other pelagic longline fisheries that fished in areas having a sea turtle abundance similar to that in the South China Sea (Chaloupka *et al.* 2004*b*; Eguchi *et al.* 2007; Wallace *et al.* 2010), which caught as much as 83 sea turtles per vessel per year for tropical Atlantic Ocean fisheries (Gilman *et al.* 2007;

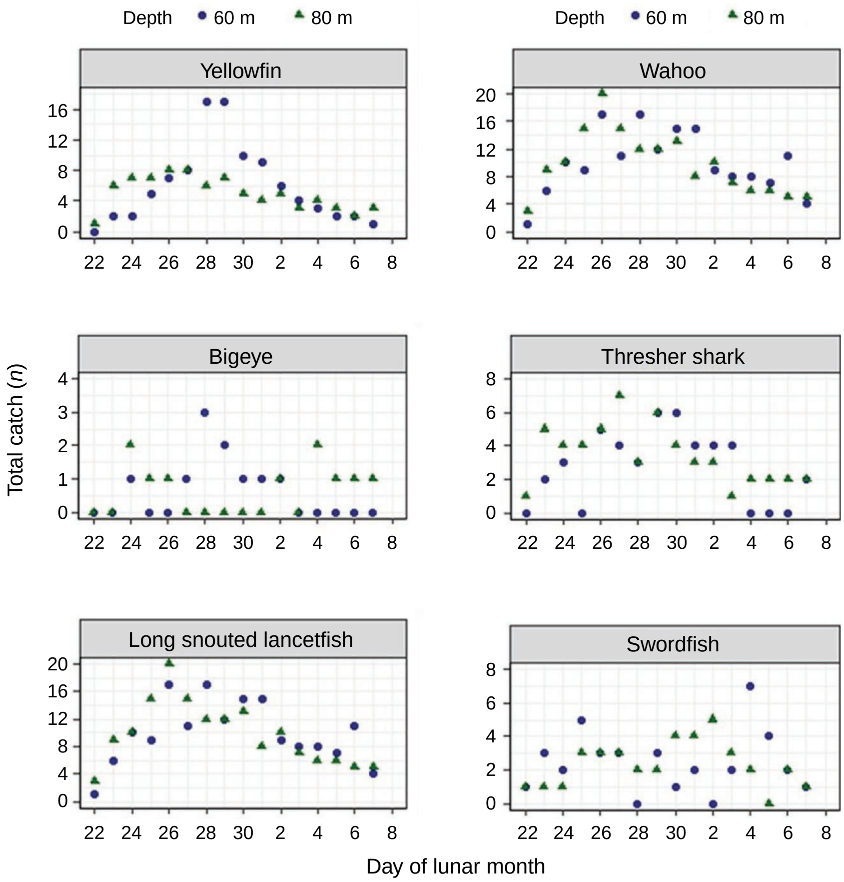


Fig. 5. The nightly catch of different species caught at 60- and 80-m depths relative to the lunar phases, with pooled data for three trips.

Table 6. The effect of lunar phases on the catch of different species, by using GAMs, represented in Eqn 2.

Species	*n*	GCV	Deviance explained	AICc	Predictor	d.f.$_e$	d.f.	χ^2	*P*
Yellowfin tuna	180	0.9	13.4%	490.8	Moonphase	1.369	3	16.16	<0.001
Bigeye tuna	180	0.1	10.1%	100.1	n.a.	n.a.	n.a.	n.a.	n.a.
Long snouted lancetfish	180	1.5	12.8%	578.6	Moonphase	1.009	3	4.9	0.016
Wahoo	180	1.5	8.0%	578.2	n.a.	n.a.	n.a.	n.a.	n.a.
Thresher shark	180	0.4	10.4%	335.9	Moonphase	1.038	3	5.31	0.013
Swordfish	180	0.4	4.0%	324.9	n.a.	n.a.	n.a.	n.a.	n.a.

n.a., not applicable, where lunar phase variable did not affect the catch.

Gilman and Huang 2017), 488 individuals for 54 sets along the Costa Rica coast (Swimmer *et al.* 2011), and 0.2 sea turtles were caught per 1000 hooks for longline fishery in Hawaii (Gilman *et al.* 2007). This is not surprising, because sea turtles are highly migratory species and rely heavily on their visual senses in their search for food (Swimmer and Brill 2006; Swimmer *et al.* 2020), and pelagic longlines fish a larger area than does PL fishery, i.e. as much as two-thirds of the world's oceans (Food and Agriculture Organization of the United Nations 2001). Thus, sea turtles are highly vulnerable to capture by longlines (Swimmer and Brill 2006).

Our results showed that C-hooks significantly reduce the bycatch of sea turtle compared with JT-hooks. This is consistent with other studies that have demonstrated improvement in bycatch mitigation for sea turtle when using large C-hooks with a small (<10°) offset, fished with large-sized baits, and deep-deployment of pelagic longlines (Watson *et al.* 2005; Gilman *et al.* 2006, 2007; Kerstetter and Graves 2006; Ward *et al.* 2009; Sales *et al.* 2010; Curran and Bigelow 2011; Pacheco *et al.* 2011; Swimmer *et al.* 2011; Huang *et al.* 2016). Although fishers were required to remove the hooks before sea turtles were returned to the waters, in many cases, hooks were located deeply in the throat and it was not possible to remove the hook. In those instances, fishers released sea turtles by cutting the branch line. There was not a quantitative

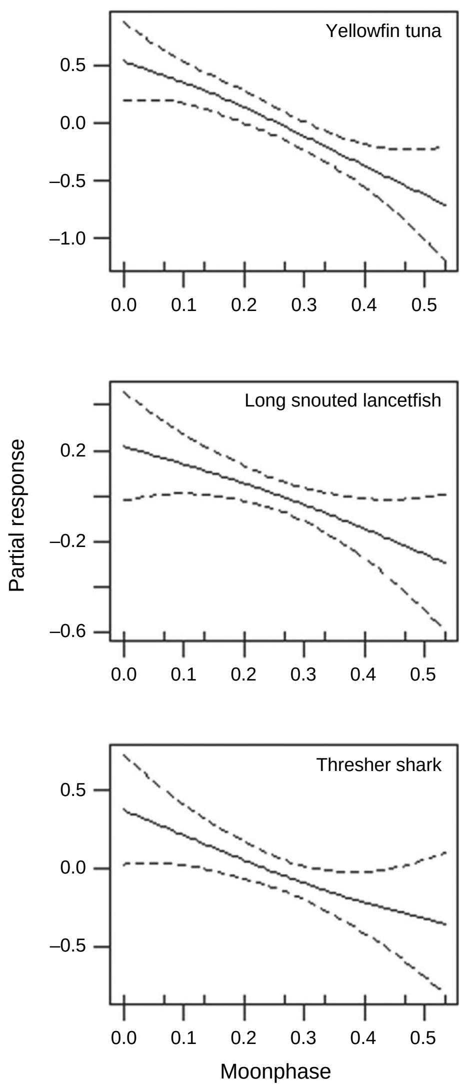


Fig. 6. Partial response curves obtained from the GAMs for the catch of yellowfin tuna, long snouted lancetfish, and thresher shark caught during the onboard research, in relation to moon phases. None of predictors was significant for the other species. All graphs show the partial effects of each significant predictor on the catch. Values above 0 indicate a positive effect of the predictor on the catch.

estimation of the proportion of post-release survival; however, post-release mortality that was tracked using satellite telemetry was believed to be high because of hook injuries without hook removals (Chaloupka *et al.* 2004*a*). A substantial number of studies have shown that the mortality rates are lower for C-hooks than for JT-hooks (Chaloupka *et al.* 2004*a*; Watson *et al.* 2005; Swimmer *et al.* 2014). All sea turtles caught in this study swam away immediately when they were released. However, we did not estimate the post-release mortality rate that required efforts. Additionally, studies have shown that mouth-hooked turtles have higher post-hooking survival prospects than have more deeply hooked turtles (Gilman *et al.* 2006). Our results showed that 69% of sea turtles were hooked in the throat with the use of JT-hooks (57.2 mm long × 30.3 mm wide), whereas all individuals caught with C-hooks (62.7 mm long × 43 mm wide) were hooked in the mouth, where the hook could also be removed more easily. Thus, the use of C-hooks not only reduced the number of sea turtles incidentally captured, it could also improve the post-release survival rate. Hook sizes also affected bycatch rates and the hooking location, in that most turtles easily swallowed the 40-mm-wide J-hook, but the 49-mm-wide C-hook resulted in turtles being most frequently hooked in the mouth (Gilman *et al.* 2006).

Whereas the PL fishery relies on above-water lights to attract target species (Nguyen and Tran 2014; Tran 2014), our study showed that bycatch rates of sea turtles increased with the higher amount of surface light power used. Previous studies showed that underwater lights play a role in attracting target species such as swordfish, marlin and tuna to pelagic longlines (Afonso *et al.* 2021), but might affect the capture of sea turtles (Witzell 1999). However, how much sea turtles are affected is unclear, and variable results have been found. For example, sea turtles are attracted to light used by lightsticks (Lohmann *et al.* 2006; Wang *et al.* 2007), whereas Gless *et al.* (2008) showed the opposite and stated that there were too many confounding factors to conclude that underwater lights attract sea turtles to pelagic longlines. Fishing lights have been shown to affect fish foraging and schooling behaviour, spatial distribution, migration, predation risk and reproduction. When the density of predators was high, fish predation occurred rapidly when the fishing lights were turned on (Rich and Longcore 2005). By contrast, predators frequently failed to catch preys under dark conditions (Thompson 2013). These unnatural behaviours have a potential effect on top–down-regulation of fish populations (Becker *et al.* 2013). More research on the effect of the surface fishing light on the vulnerability of threatened species and marine mammals is therefore recommended.

Selectivity of PL is largely influenced by the hook size (Gilman *et al.* 2006). However, the catching performance can be fishery-and species-specific (Gilman *et al.* 2018). Our study showed that C-hooks that were wider than the JT-hook, caught more larger yellowfin tuna. Findings were consistent with Gilman *et al.* (2018) who showed that larger and potentially more valuable larger yellowfin and bigeye tunas were captured on the large C-hook than on the narrower hooks. Alós *et al.* (2008) reported that large hooks were more size-selective, but had lower catch rates. Although our study showed that there were no differences in catch rates between C-hooks and JT-hooks in terms of the number of fish caught, the landing volume of C-hooks was 18% higher because of larger fish being caught. This warrants the economic benefit for fishers once they change the traditional JT-hooks to C-hooks.

It can be argued that the data of sea turtles in the dockside collected from the fishing logbook might be highly

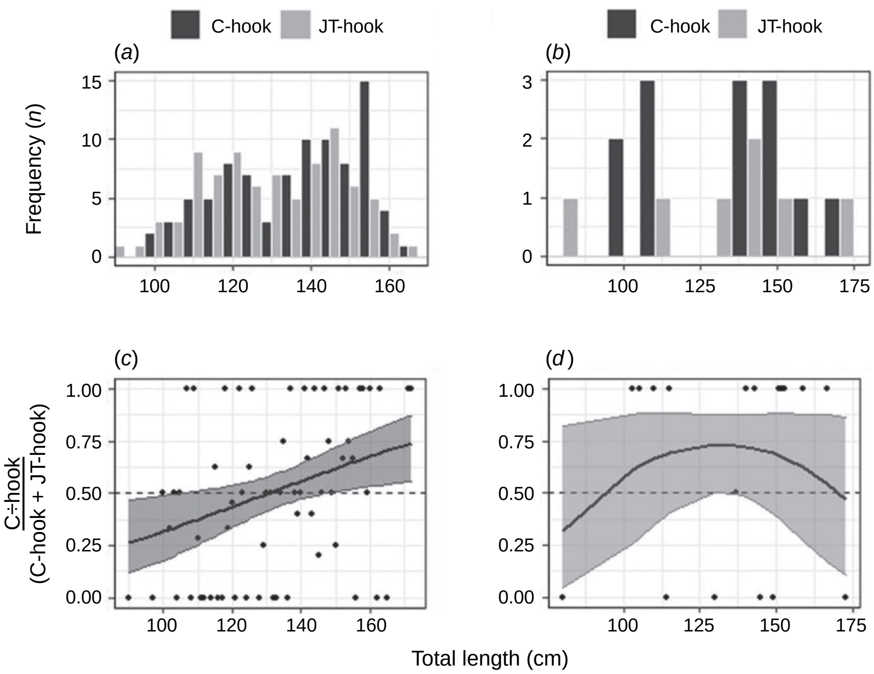


Fig. 7. Length–frequency distribution of (*a*) yellowfin tuna and (*b*) bigeye tuna captured in the different hook type treatments. GLMM results for the proportion of the total catch retained by C-hooks compared with JT-hooks for (*c*) yellowfin tuna and (*d*) bigeye tuna. Black dots indicate observed proportions (C-hook ÷ (C-hook + JT-hook)) for yellowfin tuna (*c*) and bigeye tuna (*d*) in the C-hooks and JT-hooks. The horizontal dashed line at 0.5 determines equal efficiency of both hook type treatments (*c* and *d*). A proportion greater than 0.5 indicates that more fish were caught by C-hooks, and *vice versa*, i.e. a value of 0.75 means that 75% of fish were caught by the C-hooks and 25% by the JT-hooks. The bold lines (*c* and *d*) represent the modelled mean curves at a given length class, whereas the grey shaded areas are the 95% confidence interval. Where confidence intervals overlap 0.5, there is no statistically significant difference in catch-at-length between C-hooks and JT-hooks at the given length class (no size-based selectivity).

Table 7. GLMM results for the C-hooks *v.* JT-hooks comparison.

Species	Model	AICc	Log-likelihood	Deviance	d.f.	Parameter	Estimate	s.e.	z-value	*P*
Yellowfin tuna	Constant	182.8	−89.3	178.7	102	β_0	0.07	0.15	0.46	0.649
	Linear[A]	177.1	−85.4	170.9	101	β_0	−2.03	0.82	−2.48	0.0131
						β_1	0.02	0.01	2.56	0.0104
	Quadratic	179	−85.3	170.6	100	β_0	0.82	8.66	0.10	0.924
						β_1	−0.04	0.13	−0.29	0.775
						β_2	0.00	0.00	0.47	0.637
	Cubic	180.7	−85	170.1	99	β_0	−38.78	1.23	−31.64	<0.001
						β_1	0.89	0.01	93.84	<0.001
						β_2	−0.01	0.00	−420.02	<0.001
						β_3	0.00	0.00	14.19	<0.001
Bigeye tuna	Constant	35.9	−12.9	25.9	17	β_0	0.62	0.47	1.32	0.187
	Linear	33.5	−12.9	25.9	16	β_0	0.13	2.68	0.05	0.961
						β_1	0.00	0.02	0.19	0.853
	Quadratic[A]	30.6	−12.5	25.1	15	β_0	−10.47	2.71	−3.86	<0.001
						β_1	0.17	0.02	8.33	<0.001
						β_2	0.00	0.00	−13.95	<0.001
	Cubic	39.3	−12.4	24.7	14	β_0	−40.23	2.91	−13.82	<0.001
						β_1	0.91	0.02	41.62	<0.001
						β_2	−0.01	0.00	−142.49	<0.001
						β_3	0.00	0.00	4.07	<0.001

[A]The selected model with the lowest AICc and all model parameters being statistically significant.
d.f., degrees of freedom; s.e., standard error of the estimate.

variable and unrealistic. However, all processes were inspected by authorities and observers, which have been approved by South-east Asian Fisheries Development Center and European Commission (Latun *et al.* 2019*a*, 2019*b*). Logbook records were consistently performed by experimental vessels and control vessels, which eliminated the variation, noises and bias. In addition, the number of sea turtles caught during the onboard research was consistent with the data obtained from the logbook. All offshore licenced fishery harvesters in Vietnam are required to record and report all species caught, fishing location, and other information on a daily basis, in accordance with the national logbook system (Phung 2018, 2020). In addition to mandatory fishing logbook records, random fishing vessel inspections are conducted onboard the vessels to ensure that all required processes are fully implemented (Nguyen 2019; Phung 2020). Offences can result in fines of up to US$30 000 or fishing licence suspension (Nguyen 2019). Fishing vessels must also be fully compliant in logbook reporting to obtain their catch certificate (Phung 2018, 2020). Thus, logbooks are considered to be accurately maintained and a good representation of turtle bycatch for the fishery.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. This research did not receive any specific funding.

Acknowledgements. We acknowledge the Institute of Marine Science and Fishing Technology of Nha Trang University for providing the effort to conduct this study. This work could not have been accomplished without kind help and co-operation from fishers (listed Table 1). We also thank the *KH 96281TS* owner, skipper and crews for in-kind contribution through the use of vessel, assistance conducting the onboard research and data collection. We also extend many thanks to Dr Corey J. Morris and Jacqueline M. Hanlon for helpful discussions, improvement and review of feedback regarding the content of this paper.

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