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# Comparison of catch efficiency between the use of circle and tuna hooks in Taiwan's tuna longline fishery in the eastern Pacific Ocean

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**Abstract**

Taiwan is the world's leading country regarding tuna longline fisheries; the combined catches with those from Japan account for more than half of the global total. However, the bycatch of sea turtles, seabirds, and dolphins in longline fisheries has attracted international concern. Regarding sea turtle conservation, the use of circle hooks in longline fisheries will inevitably become a trend. Meanwhile, Taiwanese fishermen are concerned whether the use of circle hooks will have a negative impact on the catch efficiency of target species. This study was conducted to compare the catch efficiency of circle and tuna hooks by the Taiwanese commercial tuna longline fishing vessels in the eastern Pacific Ocean. The results indicated that if the effects of immersion time were considered, the catch rates of all groups were the same between 4.2-sun circle and tuna hooks. However, the catch rate of 4.0-sun circle hooks was significantly higher than the two types of 4.2-sun circle and tuna hooks. Regarding survival rates, fish caught with circle hooks showed higher survival rates than tuna hooks for total commercial fish, tunas and yellowfin tuna (*Thunnus albacares*). However, the survival rate was only determined at haulback; the relationship between survival rate and immersion time still needs further investigation. Regarding catch sizes, there were no significant differences in the sizes of bigeye (*Thunnus obesus)* and yellowfin tuna between circle and tuna hooks. But based solely on mean weight, the value of yellowfin tuna caught using circle hooks may be higher than those using tuna hooks. In summary, the circle hooks used in this study did not show a negative impact on the catch efficiency of Taiwanese longline fisheries, and could show a superior performance than that of tuna hooks. These results could be actively promoted in the industry through the education and training of fishermen; thus enabling Taiwan to comply with international sea turtle conservation trends.

**Keywords:** Taiwan tuna longline fishery, circle hook, tuna hook, catch rate, survival rate

## 1. Introduction

Taiwan is the world's leading country in tuna longline fisheries, and its fishing vessels can be divided according to vessel tonnage into large-scale tuna longline fishing vessels (LTLVs, i.e., vessel tonnage ≥ 100 tons or vessel length ≥ 24 m), and small-scale tuna longline fishing vessels (STLVs). Taiwan has approximately 600 LTLVs operating throughout the international waters of the three major oceans (Pacific, Atlantic, and Indian Ocean). LTLVs can also be divided according to freezing equipment into: ultra-low temperature LTLVs (vessel tonnage between 500–700 tons) and traditional LTLVs (vessel tonnage between 200–500 tons). The majority of ultra-low temperature LTLVs operate in waters at latitudes within 20° North and South in the three major oceans; their main catches are tropical tuna species, such as bigeye and yellowfin tuna. Traditional LTLVs operate at latitudes within 20– 40° North and South in the three major oceans; their main catches are temperate albacore and swordfish. There are approximately 1,000 operating STLVs (vessel tonnage between 20–100 tons), mainly fishing bigeye, yellowfin, and bluefin tuna as their target species; their operation areas change depending on the fishing season at latitudes within 30° North and South in the Pacific and Indian oceans (Fisheries Agency, Council of Agriculture, Executive Yuan, 2014).

Longline fishing methods that specifically target tunas or swordfish are relatively common globally (Kerstetter and Graves, 2006). Among them, longline fishing that targets swordfish operate in shallower waters, close to sea turtle habitats, which can easily lead to a bycatch of sea turtles. However, altering the fishing water depth to avoid sea turtle bycatch affects the catch efficiency of the target species. In 1997, the deep-sea longline fishing fleets of Taiwan, Japan, and Spain captured a large number of swordfish, and the combined swordfish landings of these countries accounted for more than half of the global total (FAO, 2009). More than 680,000 tons of swordfish and tunas are landed by longline fisheries each

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year; Japan (31%) and Taiwan (26%) account for more than half of the global longline landings (Lewison et al., 2004). An assessment by Lewison et al. (2004) revealed that in 2000, global longline bycatch included >200,000 loggerhead sea turtles and 50,000 leatherback sea turtles, contributing to an 80–95% decline in the populations of these sea turtles over the last 20 years. Huang (2015) surveyed the data collected by observers for Taiwan longline fishing vessels in the Pacific Ocean from 2008 to 2013, which included 50 albacore LTLVs trips, 72 bigeye tuna LTLVs trips, and 27 STLV trips; 24.3 millions hooks in total. The results show that 123 sea turtles were hooked in total, including 40 by albacore LTLVs, 33 by bigeye LTLVs, and 50 by STLVs. In addition to sea turtle bycatch, the bycatch of longline fisheries also frequently includes seabirds, dolphins, sharks, and other species, some of which have been listed as protected species (Lawson, 1997). The bycatch of such protected species has drawn the widespread attention of various international organizations (Heppell et al., 2005).

Sea turtle conservation has become an issue of considerable importance to international organizations and must be solved urgently. The Committee on Fisheries (COFI) of the Food and Agriculture Organization of the United Nations (FAO) published “Guidelines to reduce sea turtle mortality in fishing operations” in November 2004, which recommended the use of circle hooks in longline fishing as the most effective method to reduce sea turtle bycatch. Furthermore, in 2009, the FAO recommended that longline fisheries should adopt the following methods to reduce sea turtle bycatch, which will not affect the capture of target species: (1) use of wide circle hooks; (2) use of fish rather than squid for bait; and (3) setting of hooks at depths deeper than turtle-abundant depths (40–100 m). In addition, several regional tuna conservation organizations, such as the Western and Central Pacific Fisheries Commission (WCPFC), Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas (ICCAT), and Indian Ocean Tuna

Commission (IOTC), have used the above FAO recommendations as guidelines to formulate relevant autonomous management measures. As described above, under the regulations of various international organizations, the future use of circle hooks will become a necessary conservation trend in longline fishing operations that specifically target swordfish or tunas.

The structure of hooks can be divided into four parts: the eye, shank, bend, and point (Bjordal and Løkkeborg, 1996). There are obvious differences in the external appearances of circle and J-style hooks. A J-style hook has its point parallel to the shank; whereas the point of a circle hook is oriented perpendicular to the shank, some of which even have points that curve downwards in the direction of the shank. As the point of a circle hook is curved towards the eye or the shank, it is directly oriented toward the pulling force of the branch line, i.e., the pulling force on the point and branch line form a straight line. Hence, when capturing fish, the tension on the branch line can be more effectively transferred to the point of the hook, thus enabling rapid hooking through the mouth of fish. Furthermore, owing to its narrow gap, hooked fish that struggle to escape will be trapped further by the hook. Regarding the J-style hook, there is an angle between the pulling force on the branch line and tension of the point hooking through the mouth tissue of the fish. Hence, the penetrating force produced by the point will be less than the actual pulling force on the branch line. Therefore, the catch rate of circle hooks is superior to that of J-style hooks (Bjordal and Løkkeborg, 1996).

To mitigate the problem of sea turtle bycatch in longline fisheries, various regional fishery organizations have begun to advocate the use of circle hooks in the operations of these fisheries. Furthermore, various countries have also continued to perform research related to the catch efficiency of circle hooks and the reduction of sea turtle bycatch (Garrison, 2003; Watson et al., 2004; Watson et al., 2005; Gilman et al., 2006; Kerstetter et al, 2006; Yokota et al., 2006; Read, 2007; Ward et al., 2009; Curran et al., 2011; Pacheco et al., 2011; Afonso et al., 2012; Hannan et al., 2013; Coelho et al., 2015; Fernandez-Carvalho et al., 2015; Lennox et al., 2015). The majority of studies indicated that the use of circle hooks by longline fisheries led to superior outcomes in hooking target catch and reducing sea turtle bycatch than that of J-style or tuna hooks (the appearance and action principle of the two are similar).

In terms of sea turtle conservation, the use of circle hooks in the operations of longline fisheries will necessarily become a trend in conservation. Taiwanese fishermen are also very concerned about whether the use of circle hooks will have a negative impact on the catch rates of target species. Many international studies have confirmed that the use of circle hooks had a positive impact on the catch efficiency of target species in longline fisheries. However, the hook size and styles used in these studies are different from those used by the longline fishery in Taiwan, and the longline operations of each country (e.g., USA, Japan, Australia, Taiwan, etc.) are also different. In addition, Taiwanese fishermen are not well-informed about circle hooks, and have always used tuna hooks in their operations. Therefore, directly applying results from other countries to advocate the changing of hooks may not be readily accepted by the longline fishing industry in Taiwan. Therefore, the present study will investigate the tuna hooks used by Taiwanese large-scale TLVs and circle hooks that are similar in size, to compare their catch efficiency for economically important fish species.

## 2. Materials and methods

### 2.1 Experimental materials

The experiment was performed in collaboration with the Lung Soon Fishery Co., Ltd. on the company's ultra-low temperature TLV "Lung Soon No. 212". The vessel was a 575-ton commercial fishing vessel (length: 54.5 m, width: 8.6 m). Its fishing gear is common for ultra-low temperature TLVs in Taiwan, which includes a Tetoron main line 4.5 mm in diameter; two types of branch lines with lengths of 35 m and 49 m, respectively; and plastic buoys with a 10.6 inch diameter.

This vessel originally used 3.4-sun and 4.2-sun tuna hooks in its operation. In this study, 4.0-sun and 4.2-sun circle hooks were added, and the experiments were conducted with four types of hooks (Fig. 1). Five species of bait were used in the experiment: *Cololabis saira*, *Sardinella sindensis*, *Scomber japonicus*, *Decapterus maruadsi*, and *Chanos chanos*. In addition, the depth of each operation and corresponding water temperature were observed by using a Minilog temperature-depth recorder (8-bit Minilog BTR produced by Vemco Ltd., Nova Scotia, Canada; abbreviated as Vemco Minilog).

2.2 Experimental methods

On April 9, 2006, the research group traveled from Taiwan to American Samoa with the experimental materials, and boarded the Taiwanese ultra-low temperature TLV “Lung Soon No. 212” on April 20. A total of 32 fishing sets were observed from April 26 to June 6. The test area was located within 1°40′S to 9°32′S, and 130°29′W to 148°15′W, which was mainly the range of operation this vessel applied for in the eastern Pacific Ocean (waters east of 150°W).

The line-setting pattern of this research vessel was similar to that of other Taiwanese ultra-low temperature TLVs. Line-setting patterns can be divided into straight-line and spiral patterns, depending on the weather conditions and captain’s preferred fishing methods. Setting operations usually began at 1–4 AM, setting at a rate of approximately 30 baskets/h, and 170–190 baskets took approximately 6 h. At the end of the straight-line setting, the research vessel remained at the end of the line for 2–3 h, before starting hauling operations. At the end of spiral setting operations, the research vessel immediately returned to the starting position of setting (approximately 30–60 min) and began hauling operations. Setting was performed at a rate of approximately 11 baskets/h, and 180 baskets took approximately 16 h to complete. For both line-setting patterns, each basket contained 17 branch lines, the distance between branch lines was 49 m, and the length of the main line for each basket was 882 m. The 3.4-sun tuna hooks were used on four branch lines (No. 1, 2, 16, and 17) of each basket, and the length of the branch lines was 35 m. Three hook types (4.0-sun and 4.2-sun circle hooks, and 4.2-sun tuna hooks) were used for 13 branch lines (No. 3–15), and the length of the branch lines was 49 m.

To cooperate with the vessel's operation pattern and abide by the principle of not affecting the interests of commercial fishing vessels, the order of setting was fixed as follows: 4.0-sun circle hooks were used on branch lines No. 3–15 for the first 15 baskets; 4.2-sun circle hooks were used on branch lines No. 3–15 for Basket No. 16–65; 4.2-sun tuna hooks were used on branch lines No. 3–15 for Basket No. 66 onwards. The 3.4-sun tuna hooks were used on branch lines No. 1, 2, 16, and 17 on all baskets.

During setting and hauling operations, the researchers made in-situ observations of catch details for each hook per set. Due to the physical limitations of the researchers, only the first two-thirds (approximately 110–130 baskets) of each hauling operation could be recorded, our analysis is limited to the data recorded within this range.

In addition, in order to understand the relationship between catch depth and water temperature, a random basket was selected per set for the attachment of Minilog temperature-depth recorders to the Stainless Box Swivel (approximately 3.5 m above the hook) on branch lines No. 1, 3, 5, 7, and 9. The frequency of recording was 10 s/sample. The Minilog temperature-depth recorders were retrieved after hauling and the data was offloaded using a field reader to analyze the fishing depth, thermocline, and other data of each hook.

### 2.3 Analytical methods

Microsoft Office Excel 2013 and IBM SPSS Statistics 24.0 were used to process and analyze the data. The calculation and analytical methods were as follows:

(1) Analysis of catch number for each hook number in all baskets

First, the catch number for each hook number of all baskets per set was obtained. As the fishing gear of each basket had left-right symmetry, the mean catch number for hook numbers with left-right symmetry was taken, which gave the individual catch number for Hook No. 1–9 after merging the hook numbers. Then, one-way analysis of variance (ANOVA) was performed to analyze the difference in the catch number between each hook number within the baskets. If a significant difference was found in the catch number among the hook numbers, then the Tukey post-hoc test was performed for further analysis.

(2) Analysis on the relationship between fishing gear immersion time and catch rate

First, the actual immersion time of each basket per set was obtained, and divided according to the number of immersed hours. The catch number for all baskets within the unit hour was summed, divided by the corresponding total hook number within the unit hour, and multiplied by 1,000 hooks to obtain the CPUE [(catch number per h/number of hooks per h) × 1,000 hooks] for each h of fishing gear immersion per set. Then, one-way ANOVA was performed to analyze the association of spiral, straight-line, and combined operations with CPUE.

(3) Comparative analysis of CPUE among different hook types

(a) Comparison without considering immersion time of each hook type: Firstly, the CPUE of each hook type per set [(catch number per set/recorded hook number per set) × 1,000 hooks]. Then, one-way ANOVA was performed to analyze the difference in the CPUE of different hook types. If a significant difference was found in the CPUE among the different hook types, then Tukey post-hoc test was performed for further analysis.

(b) Comparison considering immersion time of each hook type: First, the immersion time and catch number for the fishing gear of each basket number per set were obtained. Based on which, the catch number per unit time for the fishing gear of each basket number (catch number per basket/immersion time per basket) was calculated, which was then multiplied by 24 h to obtain the CPUE for the fishing gear of each basket number after immersion for 24 h. Secondly, the CPUE of each hook type within their respective range of basket number was summed and averaged for each set, which provided the mean CPUE value for each hook type per set. Then, one-way ANOVA was performed to analyze the difference in the CPUE of different hook types. If a significant difference was found in the CPUE among the different hook types, then the Tukey post-hoc test was performed for further analysis.

(4) Comparative analysis of hooking location, disposition at haulback, length, and weight

(a) The number of different hooking locations for each hook type was summed across all sets; the corresponding catch disposition (alive or dead) was also summed. "Internal" hooking locations indicated that the hook had been swallowed into the animal's body, such that it could not be observed with the naked eye, and could only be found after human processing. "External" hooking locations referred to locations that could be clearly observed with the naked eye, including the cheek, eye, gill, tail, etc. Then, a chi-square test was performed to analyze the differences in the hooking location and catch disposition among different hook types.

(b) The mean length and weight of each catch type were measured for each hook type. Then, one-way ANOVA was performed to analyze the difference in the mean length and weight of each catch type among different hook types. If a significant difference was found in the catch size among the different hook types, then the Tukey post-hoc test was performed for further analysis.

## 3. Results

3.1 Catch composition

A total of 32 sets were conducted in this study, of which two sets were subjected to dolphin predation of the bait, which led to poor catch rates, and hence were not included in the records and statistical analyses. A total of 62,369 hooks were recorded in the remaining 30 sets; the recorded number of hooks for each hook type is listed in Table 1. A total of 1,260 catches and 25 species were observed during the research period (Table 2). This included 369 catches of the target species, bigeye tuna (*Thunnus obesus*), which accounted for the greatest proportion (29.29%); followed by 211 yellowfin tuna (*T. albacares*). Other catches with economic value and numbers >20 included: 61 albacores (*T. alalunga*), 49 skipjack tuna (*Katsuwonus pelamis*), 32 swordfish (*Xiphias gladius*), 28 pelagic threshers (*Alopias pelagicus*), and 22 wahoo (*Acanthocybium solandri*).

3.2 Temperature-depth relationship and catch depth

Analysis of Minilog data indicated that the mean depth of operation was approximately 110.6–294.1 m, with a corresponding water temperature of 22.5–11.4°C; the depth of each hook number within the baskets is shown in Fig. 2. In addition, analysis on the relationship between operating depth and water temperature (Fig. 3) showed that at a depth of approximately 100–180 m, water temperature decreased drastically as depth increased; whereas at a depth greater than 180 m, the layer showed a stable and low temperature. Based on this, we inferred that the thermocline was at a depth of approximately 100–180 m, and its corresponding water temperature was 22.7–13.4°C. Hence, we concluded that Hook No. 1, 2, 16, and 17 were located within the thermocline, and Hook No. 3–15 were set at a deeper layer than the thermocline.

Furthermore, owing to the limitations in the catch number, we only analyzed the catch layer (hook number) of species with >100 catches, which included bigeye tuna, yellowfin tuna, sickle pomfret (*Taractichthys steindachneri*), and pelagic stingray (*Pteroplatytrygon* *violacea*). A one-way ANOVA indicated that there were significant differences in hook number for all four species (bigeye tuna $P < 0.001$, yellowfin tuna $P < 0.001$, sickle pomfret $P < 0.001$, and pelagic stingray $P < 0.001$). The Tukey post-hoc test further showed that bigeye tuna was mainly caught at Hook Nos. 3–9, yellowfin tuna at Hook No. 1–5, sickle pomfret at Hook No. 6–9, and pelagic stingray at Hook No. 1–2 (Fig. 4).

3.3 Immersion time and catch rate

The relationship between immersion time and catch rate for each operation pattern was as follows:

(1) The immersion time of straight-line operations ranged from 3 to 15 h (only the observed basket numbers). A one-way ANOVA indicated that the CPUE of the total catch ($P < 0.001$), tunas ($P = 0.036$), bigeye tuna ($P = 0.008$), and non-tuna fish($P < 0.001$) all increased with increasing immersion time (Table 3b).

(2) The immersion time of spiral operations ranged from 8–13 h (only the observed basket numbers). A one-way ANOVA indicated that the CPUE of the total catch ($P = 0.725$), tunas ($P = 0.574$), bigeye tuna ($P = 0.935$), and non-tuna fish ($P = 0.806$) was not affected by the immersion time (Table 3c).

(3) The immersion time of overall operations ranged from 3–15 h (only the observed basket numbers). A one-way ANOVA indicated that the CPUE of the total catch ($P < 0.001$), tunas ($P = 0.092$), bigeye tuna ($P = 0.009$), and non-tuna fish ($P < 0.001$) all increased with increasing immersion time (Table 3a).

3.4 CPUE

Four hook types were used in this study, of which the setting depth of the 3.4-sun tuna hook (No. 1, 2, 16, and 17) was different from that of the other three hook types (No. 3–15). Furthermore, according to the catch depth of the four species (bigeye tuna, yellowfin tuna, sickle pomfret, and pelagic stingray), each species may have its own specific active layer.

Hence, to reduce the effects of different depth layers on catch efficiency, only the catch efficiencies of 4.0-sun circle hooks, 4.2-sun circle hooks, and 4.2-sun tuna hooks were compared.

(a) Analysis of CPUE of three hook types under different operational patterns without consideration for immersion time:

Under spiral and overall operations, one-way ANOVA indicated that there were no significant differences among the CPUE of the three hook types for the total catch ($P_{Overall} = 0.101; P_{Spiral} = 0.258$), tunas ($P_{Overall} = 0.124; P_{Spiral} = 0.249$) and non-tuna fish($P_{Overall} = 0.569; P_{Spiral} = 0.684$). In addition, comparison of the target species showed that there were no significant differences among the three hook types for bigeye tuna ($P_{Overall} = 0.095; P_{Spiral} = 0.218$) and yellowfin tuna ($P_{Overall} = 0.782; P_{Spiral} = 0.848$). The CPUE of each hook type is shown in Tables 4a and 4c.

Under straight-line operations, a one-way ANOVA indicated that there were significant differences among the CPUE of the three hook types for the total catch ($P_{Straight} = 0.006$) and tunas ($P_{Straight} = 0.030$), but not for non-tuna fish ($P_{Straight} = 0.050$). In addition, comparison of the target species showed that there was a difference among the three hook types for bigeye tuna ($P_{Straight} = 0.022$), but not for yellowfin tuna ($P_{Straight} = 0.448$) (Table 4b). Tukey post-hoc test indicated that the CPUE of 4.2-sun tuna hook was significantly higher than 4.0-sun and 4.2-sun circle hooks (Table 5).

(b) Considering immersion time, a one-way ANOVA indicated that under overall operations, there were significant differences among the CPUE of the three hook types for the total catch ($P = 0.002$), tunas ($P < 0.001$), and non-tuna fish ($P = 0.033$). In addition, comparison of the target species showed that there were significant differences among the three hook types for bigeye tuna ($P = 0.028$) and yellowfin tuna (*P = 0.035*). The CPUE of each hook type is shown in Table 4a. The Tukey post-hoc test indicated that the CPUE of 4.0-sun circle hooks was significantly higher than that of 4.2-sun circle hooks and 4.2-sun tuna hooks for the total catch and tunas. As for bigeye tuna, yellowfin tuna, and non-tuna fish, the performance of 4.0-sun circle hooks was superior to that of 4.2-sun tuna hooks. There was no difference in the CPUE for all species caught between 4.2-sun circle hooks and 4.2-sun tuna hooks (Table 5).

3.5 Hooking location and survival rate

Owing to the limitations in catch numbers, this study divided the catches with economic value into the following three groups for analysis: total economic fish (795 catches), tunas (681 catches), and non-tuna economic fish (114 catches). In addition, the analysis also included bigeye tuna (360 catches) and yellowfin tuna (211 catches) within the tuna category. As it was not possible to detect when the animals were caught, the catch survival rate in this study was only based on the catch disposition upon haulback.

Statistical analysis showed that external hooking location was the most common among all hook types for all groups, and its probability was 57.6–100.0%. A Chi-square test on the hooking locations among different hook types for all groups indicated only the hooking location of tunas (*P = 0.004*) showed a significant difference, whereas the remaining groups did not show significant differences ( total economic fish *P = 0.251*, non-tuna economic fish *P = 0.066*, bigeye tuna *P = 0.792*, and yellowfin tuna *P = 0.187*) (Table 6). To further understand which type of hooks led to differences in the hooking locations of tunas, a pairwise comparison of hook types was performed, and the chi-square test revealed that the probability of external hooking was 85.6% for 3.4-sun tuna hooks, which was significantly higher than the 74.3% of 4.2-sun circle hooks ($X^2$ = 7.497, $P$ = 0.006) and 72.1% of 4.2-sun tuna hooks ($X^2$ = 11.161, $P$ < 0.001). Although the probability of external hooking for 4.0-sun circle hooks was 88.0%, possibly owing to a small sample size, the results of chi-square tests did not reveal significant differences with other hook types (4.0 C vs. 4.2 C, $P$ = 0.206; 4.0 C vs. 3.4 T, $P$ = 0.991; 4.0 C vs. 4.2 T, $P$ = 0.136).

The survival rates upon haulback among the hook types for all groups were approximately 12.7%–57.7%. A Chi-square test (Table 7) indicated that there were significant differences among different hook types for the survival rate of total economic fish ($P$ < 0.001), tunas ($P$ = 0.005), and yellowfin tuna ($P$ < 0.001); but not for bigeye tuna ($P$ = 0.452) and non-tuna economic fish ($P$ = 0.194). To further understand which of the three catch groups led to a significant difference in the results, pairwise comparisons were performed among the hook types, and the chi-square test results were as follows:

(a) Total economic fish: The survival rate for 4.2-sun tuna hooks was 25.8%, which was significantly lower than the 44.8% of 4.0-sun circle hooks ($X^2$ = 3.894, $P$ = 0.048), 36.8% of 4.2-sun circle hooks ($X^2$ = 7.510, $P$ = 0.006), and 41.6% of 3.4-sun tuna hooks ($X^2$ = 14.757, $P$ < 0.001).

(b) Tunas: The survival rate for 4.2-sun tuna hooks was 25.7%, which was significantly lower than the 37.6% of 4.2-sun circle hooks ($X^2$ = 7.836, $P$ = 0.005) and 39.1% of 3.4-sun tuna hooks ($X^2$ = 8.844, $P$ = 0.003).

(c) Yellowfin tuna: The survival rate for 4.2-sun tuna hooks was 12.7%, which was significantly lower than the 55.6% of 4.0-sun circle hooks ($X^2$ = 7.419, $P$ = 0.006), 35.8% of 4.2-sun circle hooks ($X^2$ = 9.322, $P$ = 0.002), and 57.7% of 3.4-sun tuna hooks ($X^2$ = 32.596, $P$ < 0.001). In addition, the survival rate of 4.2-sun circle hooks was also significantly lower than that of 3.4-sun tuna hooks ($X^2$ = 6.026, $P$ = 0.014).

### 3.6 Catch length and weight

Owing to the limitations in catch numbers, we only compared the length and weight of economic species with >100 catches (bigeye tuna and yellowfin tuna) among different hook types. Regarding bigeye tuna, 4.0-sun circle hooks gave the highest mean length of 131.88 cm and weight of 43.00 kg; whereas 3.4-sun tuna hooks gave the lowest mean length of 123.27 cm and weight of 34.82 kg. A one-way ANOVA indicated that there were no significant differences in the mean length ($F$ = 0.382, $P$ = 0.766) and weight ($F$ = 0.551, $P$ = 0.648) among the four hook types. Regarding yellowfin tuna, 4.0-sun circle hooks gave the highest mean length of 125.67 cm and weight of 27.22 kg; whereas 4.2-sun tuna hooks gave the lowest mean length of 116.48 cm and weight of 22.85 kg. A one-way ANOVA indicated that there were no significant differences in the mean length ($F$ = 1.963, $P$ = 0.121) and weight ($F$ = 1.225, $P$ = 0.302) among the four hook types (Table 8). In addition, based on the length and weight distributions of bigeye and yellowfin tuna (Figure 5), we can noted that the weight of both species increased exponentially with increasing length.

## 4. Discussion

### 4.1 Hook setting method and fishing gear immersion time

The hook setting method used in this study was different from those of other studies. For example: in the analysis by Garrison (2003) on the pelagic longline fishery in the Gulf of Mexico between 1992–2002, 416 sets involved the use of circle hooks (13/0, 14/0, 15/0, and 16/0), and another 1,386 sets involved J-style hooks (7/0, 8/0, and 9/0). Bolten and Bjorndal (2004) used 16/0 non-offset circle hooks, 16/0 offset circle hooks and 18/0 offset circle hooks, with the three hook types set in an alternating pattern (A-B-C-A-B-C). Bolten and Bjorndal (2005) used 16/0 non-offset circle hooks, 18/0 non-offset circle hooks and 3.6-sun Japanese tuna hooks, with the three hook types set in an alternating pattern (A-B-C-A-B-C). Kerstetter and Graves (2006) used 16/0 non-offset circle hooks and 9/0 10° offset J-style hook, with the 2 hook types deployed in an alternating pattern (C-J-C-J). Yokota et al. (2006) used 3.8-sun tuna hooks, 4.3-sun circle hooks, and 5.2-sun circle hooks, and changed the hook type every five baskets. Fernandez-Carvalho et al. (2015) used 17/0 non-offset circle hooks, 17/0 offset circle hooks, and 9/0 offset circle hooks, and changed the hook type every 70–80 hooks.

However~~,~~ our study was conducted based on the Taiwanese commercial fishing vessel's actual operational patterns. A mean number of 2,079 hooks was observed per set, which is higher than the mean number of hooks in other studies. For example: Bolten and Bjorndal (2004) had 1,573 hooks/set (75,511 hooks across 48 sets), Bolten and Bjorndal (2005) had 1,513 hooks/set (40,838 hooks across 28 sets), Watson (2005) had 874 hooks/set (427,382 hooks across 489 sets), Kerstetter and Graves (2006) had 540 hooks/set (45,900 hooks across 85 sets), Yokota et al. (2006) had 935 hooks/set (48,600 hooks across 52 sets), Ward et al. (2009) had 1,252 hooks/set (95,150 hooks across 76 sets), Pacheco et al. (2011) had 617 hooks/set (50,170 hooks across 81 sets), Curran and Bigelow(2011) had 1,991 hooks/set (2,773,427 hooks across 1,393), and Fernandez-Carvalho et al. (2015) had 1,260 hooks/set (254,520 hooks across 202 sets).

There were two operational patterns in this study. The fishing gear immersion time of straight-line operations ranged from 3 to 15 h. Results of a one-way ANOVA indicated that CPUE generally increased with longer immersion times. However, for spiral operations with immersion times concentrated within 9–13 h, CPUE was not affected by fishing gear immersion time (Table 3). Therefore, this study analyzed the relation between different hook types and CPUE in considering the effect of immersion time of the fishing gear, and it is the specialty of this study.

## 4.2 Relationship of operating water temperature and depth with catch layer of target species

Holland et al. (1990) used fish aggregating devices (FAD) to evaluate the behavioral patterns of small (50–80 cm) yellowfin and bigeye tuna. Their study showed that yellowfin tuna was mainly active at depths < 100 m, and the deepest record was 150 m (corresponding to water temperature of 20°C). The main nighttime depth layer of bigeye tuna was 70–90 m (corresponding to water temperatures of 27–23°C), and its daytime depth layer was 200–240 m (corresponding to water temperatures of 17–14°C); the deepest record was 380 m (corresponding to a water temperature of 9°C). Saito (1975) showed that the depth of capture of bigeye tuna in the Pacific Ocean was near or below the thermocline, where the corresponding water temperature was 15–11°C. Mohri et al. (1996) found that the main water temperature for the capture of bigeye tuna in the Indian Ocean was 16–10°C.

In the present study, the thermocline was at a depth of approximately 100–180 m, and the corresponding water temperature was approximately 22.7–13.4°C. In terms of catching bigeye tuna, the catch number for hook Nos. 3–15 in each basket was significantly higher than that for Hook No. 1, 2, 16, and 17 ($P < 0.001$). This implies that the main depth layer for catching bigeye tuna was approximately 194–294 m, and the corresponding water temperature was approximately 13.1–11.4°C. In terms of catching yellowfin tuna, the catch number for hook No. 1–5 and 13–17 in each basket was significantly higher than that for Hook No. 6–12 ($P < 0.001$). This implies that the main depth layer for catching yellowfin tuna was approximately 110–256 m, and the corresponding water temperature was approximately 22.5–12.1°C.

The studies above indicated that yellowfin and bigeye tuna each have their own preferred habitat layer, and our results for the main depth layer for catching bigeye and yellowfin tuna were similar to those of the three studies above.

### 4.3 Catch rates of each hook type

Our research results indicated that the catch rate of straight-line operations increased with increasing immersion time; whereas the catch rate of spiral operations was not affected by immersion time. To avoid the effects of immersion time on catch rate, data from spiral operations were more effective than those from straight-line operations when comparing catch rates.

Without considering the effects of immersion time, we found that under spiral operations, there were no significant differences in the CPUE of 4.0-sun circle hooks, 4.2-sun circle hooks, and 4.2-sun tuna hooks. Furthermore, when straight-line operations were added to the calculations (i.e., overall operations), there were no significant differences among the CPUE of the three hook types (Table 4). We also found that when the effects of immersion time were considered, the CPUE for total catch and tunas when using 4.0-sun circle hooks was significantly higher than that for 4.2-sun circle hooks and 4.2-sun tuna hooks. As for bigeye tuna, yellowfin tuna, and non-tuna fish, 4.0-sun circle hooks also had superior performance than 4.2-sun tuna hooks. However, there were no significant differences in the CPUE for the different catch groups between 4.2-sun circle and 4.2-sun tuna hooks (Table 5).

Many studies comparing the catch efficiency of different hook types found that for target or economic species, the catch rate of circle hooks was superior to that of J-style or tuna hooks. For example, Falterman et al. (2002) found that the catch number per 1,000 hooks using 14/0 circle hooks for all species and target species (yellowfin tuna) was 5.05 and 3.3, respectively, which was significantly higher than that using 7/0 J-style hooks (2.28 and 1.3, respectively). Prince et al. (2002) found that the hooking percentage of 7/0 circle hooks for Atlantic sailfish was 82%, which was significantly higher than that for 6/0 J-style hooks at 72%. Bolten and Bjorndal (2004, 2005) showed that the catch rates of circle hooks (16/0–18/0) for blue sharks may be higher than that for 9/0 J-style and 3.6-sun tuna hooks. Kerstetter and Graves (2006) found that the CPUE for tuna using 16/0 circle hooks was 49.5 per 1,000 hooks, which was significantly higher than that using 9/0 J-style hooks (38.0 per 1,000 hooks); regarding yellowfin tuna, the CPUE for 16/0 circle hooks (10.7 per 1,000 hooks) was significantly higher than that for J-style hooks (6.4 per 1,000 hooks). In addition, the study by Kerstetter et al. (2006), which compared the use of circle and J-style hooks in South Atlantic longline fisheries, showed the performance of 18/0 circle hooks was superior to 9/0 J-style hooks for the catch rates of all catch (51.8 vs. 38.6), bigeye tuna (10.3 vs. 6.9), yellowfin tuna (6.4 vs. 2.8), and swordfish (11.7 vs. 8.6). The differences were significant for the catch rates of all species, yellowfin tuna and swordfish. Yokota et al. (2006) showed that the catch rates for blue shark using 4.3-sun and 5.2-sun circle hooks were higher than that for 3.8-sun tuna hooks, but the difference was not significant. Ward et al. (2009) found that generally, the catch per 1,000 hooks for circle hooks (13/0–18/0) was 15.66, which was higher than that the 13.24 of J-style and tuna hooks (2.8-sun–3.5-sun). Pacheco et al. (2011) showed that the CPUE of tuna for 18/0 circle hooks was significantly higher than that for 9/0 J-style hooks, which was mainly due to the significant difference in the catch rate of bigeye tuna ($C_{hook}$23.02 vs. $J_{hook}$16.6). Furthermore, although the catch rates for billfish were not significantly different between the two hook types, for Atlantic sailfish alone, the catch per 1,000 J-style hooks (4.35) was significantly higher than that for circle hooks (0.6).

Conversely, the results of numerous studies have not found significant differences in the catch rates of different hook types. For example: Curran and Bigelow (2011) showed that when comparing the catch rates of different catches, 3.6-sun and 9/0 J-style hooks showed higher catch rates than 18/0 circle hooks. However, for the target species (bigeye tuna, yellowfin tuna, and albacore), there was no significant differences in the catch rates of 18/0 circle hooks and 9/0 J-style hooks (bigeye tuna: $C_{hook}$ 4.330 vs. $J_{hook}$ 3.925; yellowfin tuna: $C_{hook}$ 1.080 vs. $J_{hook}$ 1.225; albacore: $C_{hook}$ 0.116 vs. $J_{hook}$ 0.135). Furthermore, comparison of the catch rates between 18/0 circle and 3.6-sun tuna hooks showed that aside from bigeye tuna, which did not show a significant difference ($C_{hook}$ 4.029 vs. $T_{hook}$ 3.951), 3.6-sun tuna hooks had significantly higher catch rates than 18/0 circle hooks for yellowfin tuna ($C_{hook}$

0.819 vs. $T_{hook}$ 0.936) and albacore ($C_{hook}$ 0.123 vs. $T_{hook}$ 0.177). The study by Afonso et al. (2012) indicated that for swordfish, bigeye tuna, blue shark, dolphinfish, and pelagic stingray, there were no significant differences in the catch rates between 17/0 circle and 10/0 J-style hooks. Fernandez-Carvalho et al. (2015) showed that for all target species, the difference in the catch weight (kg) per 1,000 hooks between 17/0 circle and 9/0 J-style hooks was not significant.

Although the hook-setting pattern of this study differed from those of other studies, without accounting for the effects of immersion time, the overall catch rate was not significantly different between circle and tuna hooks. This result was similar to those obtained by Curran and Bigelow (2011), Afonso et al. (2012), and Fernandez-Carvalho et al. (2015). In contrast, if we considered the effects of immersion time, the catch rate of circle hooks was superior to that of tuna hooks. This result was similar to those reported by Falterman et al. (2002), Prince et al. (2002), Bolten and Bjorndal (2004 and 2005), Kerstetter and Graves (2006), Kerstetter et al. (2006), Yokota et al. (2006), Ward et al. (2009), and Pacheco et al. (2011). Furthermore, the overall appearance of tuna and J-style hooks is similar, with only slight variations in the incline angle of the eye. That is, the eye of a J-style hook is roughly oriented upright, whereas that of a tuna hook is inclined towards the point. Therefore, whether the catch efficiency of tuna hooks is similar to that of J-style hooks remains to be investigated.

4.4 Hooking location and survival rate

Bigeye and yellowfin tuna captured by Taiwanese ultra-low temperature TLVs are mainly sold on the market as sashimi. Fish freshness and catch processing are both key factors influencing market price. If bigeye and yellowfin tuna are still alive at haulback, the bloodletting effect will be superior than when the fish are dead. Moreover, fish flesh with good bloodletting is not susceptible to brown spots, and can improve fish preservation, thereby increasing the price of the fish. In addition, if smaller-sized target or non-target species are captured, and are still alive during haulback, they can be released back to the ocean, which will have a positive effect on resource conservation.

Many studies (Orsi et al., 1993; Prince et al., 2002; Cooke et al., 2003; Cooke and Suski, 2004; Bacheler and Buckel, 2004; Horodysky and Graves, 2005; John and Syers, 2005) have shown that circle hooks can more easily hook through the cheeks of animals, which will reduce the chances of being deeply-hooked, thereby decreasing the risk of severe internal injury and death. However, a study by Bacheler and Buckel (2004) on benthic fish found that the chances of internal hooking for large J-style hooks (9/0) was significantly lower than that for small J-style hooks (5/0), hence large J-style hooks inflicted less injury on the catch. With respect to longline fisheries, Fernandez-Carvalho et al. (2015) found that there was no significant difference in mortality at haulback between 17/0 circle and 9/0 J-style hooks for bigeye thresher (*Alopias superciliosus*), crocodile shark (*Pseudocarcharias kamoharai*), smooth hammerhead (*Sphyrna zygaena*), and oceanic whitetip shark (*Carcharhinus longimanus*). Afonso et al. (2012) showed that there was no significant difference in the mortality of total catch and shark catch between 17/0 circle and 10/0 J-style hooks. The study by Curran and Bigelow (2011) indicated that the survival rates of bigeye and yellowfin tuna caught using 18/0 circle hooks were 81.8% and 58.7%, respectively, which were higher than those caught using 3.6-sun tuna hooks (77.9% and 53.6%, respectively). Pacheco et al. (2011) showed that the probability of external hooking for different catch groups using 18/0 circle hooks was 70–97%, but was relatively low when using 9/0 J-style hooks. Mortality of tuna and all catch for 9/0 J-style hooks was 55.1% and 55.4%, respectively, which was significantly higher than that for 18/0 circle hooks at 38.4% and 49.1%. Ward et al. (2009) found that the hooking location of circle hooks (14/0–16/0) and tuna hooks (2.8–3.4 sun) was mainly through the cheeks, and their survival rates were also not significantly different. In summary, the results of hooking location and catch disposition were not always consistent among different studies. This may have been owing to fish species with different characteristics (habitat environment, movement patterns, mouth type), and variations in their bait-seeking patterns (Wootton, 1989). The most crucial factor of catch mortality is hooking location, and the mortality of internal hooking is far greater than hooking through the cheek (Lukacovic and Uphoff, 2002).

Regarding our study results, the main hooking location of the four hook types was external, which is similar to the findings by Ward et al. (2009). For survival rate, circle hooks showed superior performance for economic species than 4.2-sun tuna hooks. However, 3.4-sun tuna hooks generally showed higher survival rates for all economic species than 4.2-sun tuna hooks, and even showed significant differences for total economic catch, tunas, and yellowfin tuna. Whether such results were related to the immersion times of different hook types, catch depth, or other factors still awaits further investigations. Regardless of these issues, our finding that circle hooks inflicted less injury on the catch was consistent with findings from most previous studies.

### 4.5 Length and weight of target species

Aside from fish freshness as mentioned above, one of the factors influencing the prices of bigeye and yellowfin tuna captured by Taiwanese ultra-low temperature TLVs is catch weight; heavier catch will fetch a higher unit price. The fishery company of the research vessel (Lung Soon Fishery) classifies the weight of bigeye and yellowfin tuna as follows: The prices of bigeye tuna are divided based on four weight specifications, which are, in descending order, >40, 25–40, 15–24, and 0–14 kg; the prices of yellowfin tuna are divided based on three weight specifications, which are, in descending order, >25, 15–24, and 0–14 kg.

Lukacovic and Uphoff (2002) demonstrated that using circle and J-style hooks of the same size did not lead to significant differences in catch size. In contrast, Cooke and Suiki (2004) showed that a larger hook size resulted in a larger catch size. However, these studies were limited to recreational fisheries. In terms of longline fisheries, Fernandez-Carvalho et al. (2015) found that the lengths of bigeye (114.6–115.7 cm) and yellowfin (132.9~136.4 cm) tuna caught using circle hooks (17/0) were smaller than those caught by 9/0 J-style hooks (bigeye tuna: 129.9 cm, yellowfin tuna: 146.1 cm). Curran and Bigelow (2011) showed that the lengths of bigeye (117.1 cm) and yellowfin (107.4 cm) tuna caught using 18/0 circle hooks were not significantly different from that caught using 9/0 J-style hooks (bigeye tuna: 116.7 cm, yellowfin tuna: 106.6 cm) and 3.6-sun tuna hooks (bigeye tuna: 116.2 cm, yellowfin tuna: 107.5 cm). Ward et al. (2009) found that the lengths of bigeye and yellowfin tuna caught using circle hooks (14/0–16/0) and tuna hooks (2.8–3.4 sun) were not significantly different (bigeye tuna: $C_{hook}$ 128.6 vs. $T_{hook}$ 130.4 cm; yellowfin tuna: $C_{hook}$ 121.5 vs. $T_{hook}$ 123.7 cm). Although these studies only compared catch lengths, we know from the relationship between the weight and length of bigeye tuna and yellowfin tuna that the weight of the target species will increase with increasing length. Hence, a lack of difference in catch lengths among the different hook types would imply that there might not be a difference in weight as well.

In this study, there were no differences in the catch sizes of bigeye and yellowfin tuna among the four hook types. This result is inconsistent with the findings of studies on recreational fisheries, but is similar to studies on longline fisheries by Curran and Bigelow (2011), and Ward et al. (2009). In summary, the conclusions obtained on catch size from recreational fisheries may not be completely applicable to longline fisheries. Furthermore, although there were no significant differences in the sizes of bigeye tuna among the four hook types, the mean weight of the 3.4-sun tuna hook was only 34.82 kg, which is on a different price grade to the 41.59 kg of 4.2-sun tuna hooks. However, whether the weight difference in bigeye tuna caught using tuna hooks of different sizes may have been related to the different hook setting depths still awaits further investigations. Regardless of this issue, large tuna hooks may have a better catch value for bigeye tuna than small tuna hooks. For yellowfin tuna, the catch weight of circle hooks was > 25 kg, which may have a better catch value than catches < 24 kg of tuna hooks.

## 5. Conclusion

In terms of catch rates, if the effects of immersion time are considered, then the catch rates of 4.2-sun circle hooks and 4.2-sun tuna hooks are the same for different catch groups; whereas the catch rate of 4.0-sun circle hooks is significantly higher than the two 4.2-sun hooks. Overall, the catch rates of circle hooks were superior to tuna hooks for different catch groups. With regards to survival rate, circle hooks showed higher survival rates than tuna hooks for all economic fish, tuna, and yellowfin tuna. However, survival rate was only determined at haulback; the relationship between survival rate and immersion still awaits further investigation. For catch sizes, there were no significant differences in the sizes of bigeye and yellowfin tuna between circle and tuna hooks. However, based solely on mean weight, the economic value of yellowfin tuna caught using circle hooks may be higher than those using tuna hooks. In summary, the circle hooks used in this study will not have a negative impact on the catch efficiency of Taiwanese ultra-low temperature longline fisheries, and may even show a superior performance than tuna hooks. These results can be actively promoted in the industry through the education and training of fishermen, thus enabling Taiwan to comply with international conservation trends.

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**Figure captions**

Fig. 1. 3.4-sun tuna hook (upper left), 4.2-sun tuna hook (upper right), 4.2-sun circle hook (lower right), and 4.0-sun circle hook (lower left) used in this study

Fig. 2. Mean depth of each hook number within a basket

Fig. 3. Temperature and depth relationship

Fig. 4. Distribution of hook numbers for species with catch numbers > 100: Bigeye tuna, yellowfin tuna, sickle pomfret, and pelagic stingray

Fig. 5. Relationship between weight and length in bigeye tuna (above) and yellowfin tuna (below)

Table 1. Recorded number of each hook type

| Hook type | Straight-line operations | | Spiral operations | | Overall operations | |
|---|---|---|---|---|---|---|
| | Sets | Hooks | Sets | Hooks | Sets | Hooks |
| 4.0 C | 6 | 1,084 | 11 | 2,320 | 17 | 3,404 |
| 4.2 C | 14 | 9,819 | 16 | 11,351 | 30 | 21,170 |
| 3.4 T | 14 | 6,956 | 16 | 8,054 | 30 | 15,010 |
| 4.2 T | 14 | 10,827 | 16 | 11,958 | 30 | 22,785 |
| **Sub-total** | | 28,686 | | 33,683 | | 62,369 |

17 Table 2. Catch number of each hook type

| Common name | Scientific name | Catch number | | | | | % |
|---|---|---|---|---|---|---|---|
| | | 4.0 C | 4.2 C | 3.4 T | 4.2 T | Total | |
| **Tunas** | | **25** | **208** | **178** | **279** | **690** | **54.76** |
| Bigeye tuna | *Thunnus obesus* | 16 | 147 | 12 | 194 | 369 | 29.29 |
| Yellowfin tuna | *Thunnus albacares* | 9 | 53 | 78 | 71 | 211 | 16.75 |
| Albacore | *Thunnus alalunga* | - | 6 | 45 | 10 | 61 | 4.84 |
| Skipjack tuna | *Katsuwonus pelamis* | - | 2 | 43 | 4 | 49 | 3.89 |
| **Billfish** | | **2** | **18** | **23** | **11** | **54** | **4.29** |
| Swordfish | *Xiphias gladius* | 2 | 12 | 12 | 6 | 32 | 2.54 |
| Shortbill spearfish | *Tetrapturus angustirostris* | - | 3 | 8 | 2 | 13 | 1.03 |
| Indo-Pacific blue marlin | *Makaira mazara* | - | 1 | 3 | 2 | 6 | 0.48 |
| Sailfish | *Istiophorus platypterus* | - | 1 | - | - | 1 | 0.08 |
| Striped Marlin | *Tetrapturus audax* | - | 1 | - | - | 1 | 0.08 |
| Black marlin | *Makaira indica* | - | - | - | 1 | 1 | 0.08 |
| **Shark** | | **1** | **18** | **21** | **27** | **67** | **5.32** |
| Pelagic thresher | *Alopias pelagicus* | 1 | 12 | 4 | 11 | 28 | 2.22 |
| Blue shark | *Prionace glauca* | - | 2 | 10 | 4 | 16 | 1.27 |
| Velvet dogfish | *Zameus squamulosus* | - | 3 | 2 | 10 | 15 | 1.19 |
| Shortfin mako shark | *Isurus oxyrinchus* | - | 1 | 1 | 1 | 3 | 0.24 |
| Silky shark | *Carcharhinus falciformis* | - | - | 1 | 1 | 2 | 0.16 |
| Longfin mako shark | *Isurus paucus* | - | - | 2 | - | 2 | 0.16 |
| Oceanic whitetip shark | *Carcharhinus longimanus* | - | - | 1 | - | 1 | 0.08 |
| **Other fish** | | **18** | **119** | **161** | **151** | **449** | **35.63** |
| Sickle pomfret | *Taractichthys steindachneri* | 12 | 80 | 9 | 94 | 195 | 15.48 |
| Pelagic stingray | *Pteroplatytrygon violacea* | 1 | 5 | 111 | 10 | 127 | 10.08 |
| Longnose lancetfish | *Alepisaurus ferox* | 3 | 23 | 17 | 42 | 85 | 6.75 |
| Wahoo | *Acanthocybium solandri* | - | 2 | 19 | 1 | 22 | 1.75 |
| Escolar | *Lepidocybium flavobrunneum* | - | 6 | 2 | 1 | 9 | 0.71 |
| Great barracuda | *Sphyraena barracuda* | 1 | 1 | 2 | 1 | 5 | 0.40 |
| Dolphinfish | *Coryphaena hippurus* | 1 | 2 | - | 2 | 5 | 0.40 |
| Moonfish | *Lampris guttatus* | - | - | 1 | - | 1 | 0.08 |
| **Total** | | **46** | **363** | **383** | **468** | **1,260** | **100.00** |

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Table 3. Relationship between fishing gear immersion time and CPUE

unit：CPUE

| Catch | Immersion time (h) | | | | | | | | | | | | | One-way ANOVA | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | 10-11 | 11-12 | 12-13 | 13-14 | 14-15 | *d.f.* | *F* | *P* |
| **(a)Overall operations** | | | | | | | | | | | | | | | | |
| Total catch | 8.7 | 10.0 | 8.4 | 12.5 | 18.6 | 21.5 | 17.6 | 19.8 | 21.1 | 25.1 | 24.2 | 31.5 | 33.8 | 12 | 3.51 | <0.001$^{**}$ |
| Tunas | 6.2 | 5.6 | 6.4 | 6.9 | 11.0 | 14.0 | 10.7 | 10.9 | 12.3 | 13.5 | 13.3 | 18.6 | 19.0 | 12 | 1.60 | 0.092 |
| Bigeye tuna | 2.0 | 1.5 | 3.9 | 3.9 | 4.5 | 8.1 | 5.9 | 5.9 | 5.7 | 6.6 | 7.9 | 11.3 | 10.1 | 12 | 2.28 | 0.009$^{**}$ |
| Non-tuna fish | 2.4 | 4.4 | 2.0 | 5.6 | 7.6 | 7.4 | 6.8 | 8.8 | 8.8 | 11.7 | 10.9 | 12.9 | 14.8 | 12 | 3.09 | <0.001$^{**}$ |
| **(b) Straight-line operations** | | | | | | | | | | | | | | | | |
| Total catch | 8.7 | 10.0 | 8.4 | 12.5 | 18.6 | 21.5 | 14.4 | 18.1 | 25.4 | 33.3 | 33.9 | 31.5 | 33.8 | 12 | 4.27 | <0.001$^{**}$ |
| Tunas | 6.2 | 5.6 | 6.4 | 6.9 | 11.0 | 14.0 | 11.0 | 10.2 | 14.4 | 19.3 | 20.1 | 18.6 | 19.0 | 12 | 1.91 | 0.036$^{*}$ |
| Bigeye tuna | 2.0 | 1.5 | 3.9 | 3.9 | 4.5 | 8.1 | 6.5 | 6.1 | 7.0 | 9.2 | 11.3 | 11.3 | 10.1 | 12 | 2.36 | 0.008$^{**}$ |
| Non-tuna fish | 2.4 | 4.4 | 2.0 | 5.6 | 7.6 | 7.4 | 3.5 | 7.9 | 10.9 | 14.0 | 13.8 | 12.9 | 14.8 | 12 | 3.53 | <0.001$^{**}$ |
| **(c) Spiral operations** | | | | | | | | | | | | | | | | |
| Total catch | | | | | | | 20.3 | 21.2 | 17.4 | 18.0 | 15.7 | | | 4 | 0.52 | 0.725 |
| Tunas | | | | | | | 10.5 | 11.6 | 10.4 | 8.4 | 7.3 | | | 4 | 0.73 | 0.574 |
| Bigeye tuna | | | | | | | 5.3 | 5.7 | 4.5 | 4.3 | 4.9 | | | 4 | 0.21 | 0.935 |
| Non-tuna fish | | | | | | | 9.8 | 9.6 | 7.0 | 9.6 | 8.4 | | | 4 | 0.40 | 0.806 |

*：*P<0.05*, **：*P<0.01*, Non-tuna fish = billfish + shark + other fish.

Table 4. Comparison of CPUE among 4.0-sun circle hook, 4.2-sun circle hook, and 4.2-sun tuna hook

| **Catch** | **Immersion time considered?** | **(a) Overall operations** | | | | | | | **(b) Straight-line operations** | | | | | | | **(c) Spiral operations** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CPUE (catch number) | | | | | | One way ANOVA *P* | CPUE (catch number) | | | | | | One way ANOVA *P* | CPUE (catch number) | | | | | | One way ANOVA *P* |
| | | 4.0 C | | 4.2 C | | 4.2 T | | | 4.0 C | | 4.2 C | | 4.2 T | | | 4.0 C | | 4.2 C | | 4.2 T | | |
| Total catch | No | 13.73 | (46) | 17.07 | (363) | 20.69 | (468) | 0.101 | 11.87 | (12) | 13.56 | (133) | 26.49 | (285) | $0.006^{**}$ | 14.74 | (34) | 20.15 | (230) | 15.61 | (183) | 0.258 |
| | Yes | 1.13 | | 0.71 | | 0.50 | | $0.002^{**}$ | | | | | | | | | | | | | | |
| Tunas | No | 7.62 | (25) | 9.80 | (208) | 12.31 | (279) | 0.124 | 9.67 | (10) | 8.55 | (83) | 16.64 | (179) | $0.030^{*}$ | 6.50 | (15) | 10.89 | (125) | 8.53 | (100) | 0.249 |
| | Yes | 0.78 | | 0.41 | | 0.30 | | $<0.001^{**}$ | | | | | | | | | | | | | | |
| Bigeye tuna | No | 4.98 | (16) | 6.92 | (147) | 8.54 | (194) | 0.095 | 6.30 | (6) | 6.16 | (60) | 11.69 | (126) | $0.022^{*}$ | 4.27 | (10) | 7.59 | (87) | 5.78 | (68) | 0.218 |
| | Yes | 0.48 | | 0.29 | | 0.21 | | $0.028^{*}$ | | | | | | | | | | | | | | |
| Yellowfin tuna | No | 2.63 | (9) | 2.50 | (53) | 3.12 | (71) | 0.782 | 3.57 | (4) | 2.29 | (22) | 4.27 | (46) | 0.448 | 2.24 | (5) | 2.69 | (31) | 2.11 | (25) | 0.848 |
| | Yes | 0.22 | | 0.11 | | 0.08 | | $0.035^{*}$ | | | | | | | | | | | | | | |
| Non-tuna fish | No | 6.10 | (21) | 7.28 | (155) | 8.37 | (189) | 0.569 | 2.20 | (2) | 5.01 | (50) | 9.85 | (106) | 0.050 | 8.23 | (19) | 9.26 | (105) | 7.08 | (83) | 0.684 |
| | Yes | 0.39 | | 0.22 | | 0.16 | | $0.033^{*}$ | | | | | | | | | | | | | | |

* : $P<0.05$, ** : $P<0.01$, Non-tuna fish = billfish + shark + other fish.

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Table 5. Post-hoc test results of significant differences in CPUE among 4.0-sun circle hook, 4.2-sun circle hook, and 4.2-sun tuna hook

Unit: *p value*

| Immersion time considered? | Operation type | Catch | Tukey HSD | | |
|---|---|---|---|---|---|
| | | | 4.0 C vs. 4.2 C | 4.0 C vs. 4.2 T | 4.2 C vs. 4.2 T |
| No | Straight-line | Total catch | 0.948 | $0.029^{*}$ | $0.011^{*}$ |
| No | Straight-line | Tunas | 0.956 | 0.190 | $0.031^{*}$ |
| No | Straight-line | Bigeye tuna | 0.998 | 0.113 | $0.026^{*}$ |
| Yes | Overall | Total catch | $0.035^{*}$ | $< 0.001^{**}$ | 0.330 |
| Yes | Overall | Tunas | $0.005^{**}$ | $< 0.001^{**}$ | 0.491 |
| Yes | Overall | Bigeye tuna | 0.133 | $0.021^{*}$ | 0.628 |
| Yes | Overall | Yellowfin tuna | 0.109 | $0.030^{*}$ | 0.787 |
| Yes | Overall | Non-tuna fish | 0.130 | $0.026^{*}$ | 0.694 |

* ： $P<0.05$, ** ： $P<0.01$, Non-tuna fish = billfish+shark+other fish.

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Table 6. Comparison of probability for external hooking among different hook types

| Catch | Hook style | | | | | | | | $X^2$ value | $P$ value | Tunas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 C | | 4.2 C | | 3.4 T | | 4.2 T | | | | | | |
| | % | Number (External / Total) | % | Number (External / Total) | % | Number (External / Total) | % | Number (External / Total) | | | Chi-square test | $X^2$ value | $P$ value |
| Total economic catch | 86.21 | (25 / 29) | 73.97 | (179 / 242) | 78.54 | (183 / 233) | 73.20 | (213 / 291) | 4.101 | 0.251 | 4.0 C vs. 4.2 C | 1.602 | 0.206 |
| Tunas | 88.00 | (22 / 25) | 74.29 | (156 / 210) | 85.63 | (149 / 174) | 72.06 | (196 / 272) | 13.554 | $0.004^{**}$ | 4.0 C vs. 3.4 T | $<0.001^{**}$ | 0.991 |
| Bigeye tuna | 81.25 | (13 / 16) | 73.47 | (108 / 147) | 70.00 | (7 / 10) | 70.59 | (132 / 187) | 1.037 | 0.792 | 4.0 C vs. 4.2 T | 2.219 | 0.136 |
| Yellowfin tuna | 100.00 | (9 / 9) | 77.36 | (41 / 53) | 84.62 | (66 / 78) | 74.65 | (53 / 71) | 4.807 | 0.187 | 4.2 C vs. 3.4 T | 7.497 | $0.006^{**}$ |
| Non-tuna economic fish | 75.00 | (3 / 4) | 71.88 | (23 / 32) | 57.63 | (34 / 59) | 89.47 | (17 / 19) | 7.190 | 0.066 | 4.2 C vs. 4.2 T | 0.298 | 0.585 |
| | | | | | | | | | | | 4.2 C vs. 3.4 T | 11.161 | $<0.001^{**}$ |

* : $P<0.05$, ** : $P<0.01$, ALL economic catch includes tuna, billfish, shark and other fish with commercial value (i.e., wahoo, escolar, great barracuda, dolphinfish and moonfish).

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Table 7. Comparison of survival rate at haulback among different hook types

| Catch | Hook style | | | | | | | | | | | P-value | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4.0 C | | 4.2 C | | 3.4 T | | 4.2 T | | | | | | | |
| | % | Number (Live / Total) | % | Number (Live / Total) | % | Number (Live / Total) | % | Number (Live / Total) | $X^2$ value | $P$ Value | Chi-square test | ALL economic catch | Tunas | Yellowfin tuna |
| Total economic catch | 44.83 | (13 / 29) | 36.78 | (89 / 242) | 41.63 | (97 / 233) | 25.77 | (75 / 291) | 16.982 | <0.001** | 4.0 C vs. 4.2 C | 0.398 | 0.535 | 0.452 |
| Tunas | 44.00 | (11 / 25) | 37.62 | (79 / 210) | 39.08 | (68 / 174) | 25.74 | (70 / 272) | 12.634 | 0.005** | 4.0 C vs. 3.4 T | 0.742 | 0.801 | 1.000 |
| Bigeye tuna | 37.50 | (9 / 16) | 38.10 | (56 / 147) | 50.00 | (5 / 10) | 31.55 | (59 / 187) | 2.630 | 0.452 | 4.0 C vs. 4.2 T | 0.048* | 0.084 | 0.006** |
| Yellowfin tuna | 55.56 | (5 / 9) | 35.85 | (19 / 53) | 57.69 | (45 / 78) | 12.68 | (9 / 71) | 33.721 | <0.001** | 4.2 C vs. 3.4 T | 0.279 | 0.851 | 0.014* |
| Non-tuna economic fish | 50.00 | (2 / 4) | 31.25 | (10 / 32) | 49.15 | (29 / 59) | 26.32 | (5 / 19) | 4.710 | 0.194 | 4.2 C vs. 4.2 T | 0.006** | 0.005** | 0.002** |
| | | | | | | | | | | | 4.2 C vs. 3.4 T | <0.001** | 0.003** | <0.001** |

* : $P<0.05$, ** : $P<0.01$, ALL economic catch includes tuna, billfish, shark and other fish with commercial value (i.e., wahoo, escolar, great barracuda, dolphinfish and moonfish).

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Table 8. Comparison of catch weight and length of bigeye tuna and yellowfin tuna among different hook types

| Catch | | Hook style | | | | | | | | One-way ANOVA | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 4.0 C | | 4.2 C | | 3.4 T | | 4.2 T | | | |
| | | Mean (cm or kg) | N | Mean (cm or kg) | N | Mean (cm or kg) | N | Mean (cm or kg) | N | *F* value | *P* value |
| Bigeye tuna | Length | 131.88 | 16 | 130.75 | 147 | 123.27 | 11 | 131.86 | 194 | 0.382 | 0.766 |
| | Weight | 43.00 | | 39.12 | | 34.82 | | 41.59 | | 0.551 | 0.648 |
| Yellowfin tuna | Length | 125.67 | 9 | 121.63 | 51 | 120.42 | 76 | 116.48 | 71 | 1.963 | 0.121 |
| | Weight | 27.22 | | 25.90 | | 23.88 | | 22.85 | | 1.225 | 0.302 |