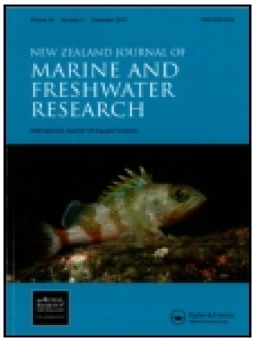

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Environmental preferences of *Alopias superciliosus* and *Alopias vulpinus* in waters near the Marshall Islands

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This paper reports on a survey carried out in waters near Marshall Islands and on the analysis of catch rates of bigeye thresher shark, *Alopias superciliosus*, and thresher shark, *Alopias vulpinus*. The optimum swimming depth, water temperature, salinity and dissolved oxygen range of bigeye thresher sharks were identified as 240–360 m, 10–16°C, 34.5–34.7 and 3.0–4.0 ml/l, respectively, while for thresher sharks they were 160–240 m, 18–20°C, 34.5–34.8 and 1.0–1.5 ml/l, respectively, during daytime. The bigeye thresher shark and thresher shark were widely distributed in areas where the dissolved oxygen was higher than 0.5 ml/l. Some mitigation measures were recommended to reduce the bycatch of bigeye thresher shark and thresher shark, including avoiding fishing in peak areas and periods of shark abundance, using fish as bait and using nylon monofilament leaders. Furthermore, the hook depth data could be input into the 'habitat model' to standardise the shark catch per unit effort (CPUE).

Keywords: bigeye thresher shark; *Alopias superciliosus*; thresher shark; *Alopias vulpinus*; environmental preferences; longline; Marshall Islands; bycatch

Introduction

Sharks can be found in every corner of the ocean and play an important role in marine ecosystem functions. The ecological value, scientific value and economic value of sharks are high. The conservation and management of sharks are very important in the protection of marine ecosystem, maintenance of biodiversity and sustainable utilisation of resources. However, sharks often have a low stock-recruitment relationship and a long stock-recovery time after overfishing owing to their late sexual maturity and low fecundity, even though they generally have low natural mortality and their populations have a complex spatial structure (FAO 2000). Research on environmental preferences of sharks can reduce incidental catch of sharks during commercial fishing operations and benefit the conservation of shark species.

Many methods have been used to study shark environmental preferences and migration, including tagging (Nakano et al. 2003; Weng & Block 2004; Sims et al. 2005; Hulbert et al. 2006; Wilson et al. 2007; Rowat & Gore 2007; Hsu et al. 2007), catch analysis (Jakobsdóttir 2001; Campana & Joyce 2004; Garla et al. 2006; Liu 2007) and experimental observations of animals in tanks (Carlson et al. 1999). Nakano et al. (2003) used acoustic telemetry to identify the short-term horizontal and vertical movement

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patterns of bigeye thresher shark (*Alopias superciliosus*) in the eastern Pacific Ocean. Weng & Block (2004) used the pop-up satellite archival tags to study the diel vertical migration of bigeye thresher shark in Hawaiian waters and the Gulf of Mexico. Liu (2007) analysed the biology and hooked water depth of some bycatch species in the eastern Pacific longline fishery and identified the bigeye thresher shark's optimum water depth (sampling range: 0–320 m), temperature and salinity.

Numerous factors may influence shark distribution and migration, e.g. depth, water temperature, salinity, current and bottom topography (Sims et al. 2005; Hulbert et al. 2006; Campana & Joyce 2004; Garla et al. 2006). The environment of shark habitat is very complex, both spatially and temporally. Mechanisms of shark migration have not been determined; Sims et al. (2005) suggested that the migration might be related to the behaviour of zooplankton.

Data from both tagging and catch analysis methods allowed only limited interpretation of the associations between animal movement and the environment. Tagging studies have mainly been aimed at a specific growth stage of particular shark species to understand their habitat and migration by studying its location, depth and water temperature. This method is effective for understanding shark long-distance migration, but sample sizes are usually small (usually sampling one shark in a region). On the other hand, the catch analysis method provides a large number of data for studying shark habitat and migration patterns, but there are uncertainties in the catch data.

We evaluate the habitat of the bigeye thresher shark and thresher shark (*Alopias vulpinus*) observed in waters near Marshall Islands. Using the codes of the hooks that caught these species, we determined the depth of the animal. Specifically, we predicted the hook depth by using multiple regression models based on environmental variables, including gear drift velocity over the ground, wind speed and wind direction measured at sea, and fishing gear specifications. The results derived from this study can improve the accuracy of estimations of the preferred depth, temperature, salinity and dissolved oxygen of the bigeye thresher shark and thresher shark, which can contribute to shark conservation by reducing species' incidental catch, and will lead to more informed choices of environmental variables considered in CPUE (catch per unit effort) standardisation.

Materials and methods

Fishing vessel and fishing grounds

Data were collected from operations on tuna longliner Shenliancheng No. 719, a steel vessel 32.28 m long, 5.70 m wide and 2.60 m in registered depth. The vessel had gross tonnage of 97 tons and was powered by a 220-kW main engine. Fishing was conducted from 27 October 2006 to 29 May 2007 near the Marshall Islands, using the vessel's super spool longlining system, with a total of 69 sampling sites. The fishing vessel was targeting bigeye tuna (*Thunnus obesus*), with a total bycatch of 78 bigeye thresher sharks and 87 thresher sharks during the observation trips (Fig. 1). The peak areas and periods of sharks abundance within the Marshall Islands' exclusive economic zone (EEZ) were 8–11°N, 172–176°E, from April to May for bigeye thresher shark, and 9–12°N, 163–165°E, 6–8°N, 165–168°E, from November to December for thresher shark. We identified and recorded the codes of the hooks on which were caught 71 bigeye thresher sharks and 72 thresher sharks. The sampling coverage of bigeye thresher shark and thresher shark was 91.0% and 82.8% (water depth and temperature), 84.6% and 79.3% (salinity), 83.3% and 79.3% (dissolved oxygen), respectively.

Fishing gear and operations

The longline gear consisted of 90 km of 4.0-mm-diameter monofilament mainline,

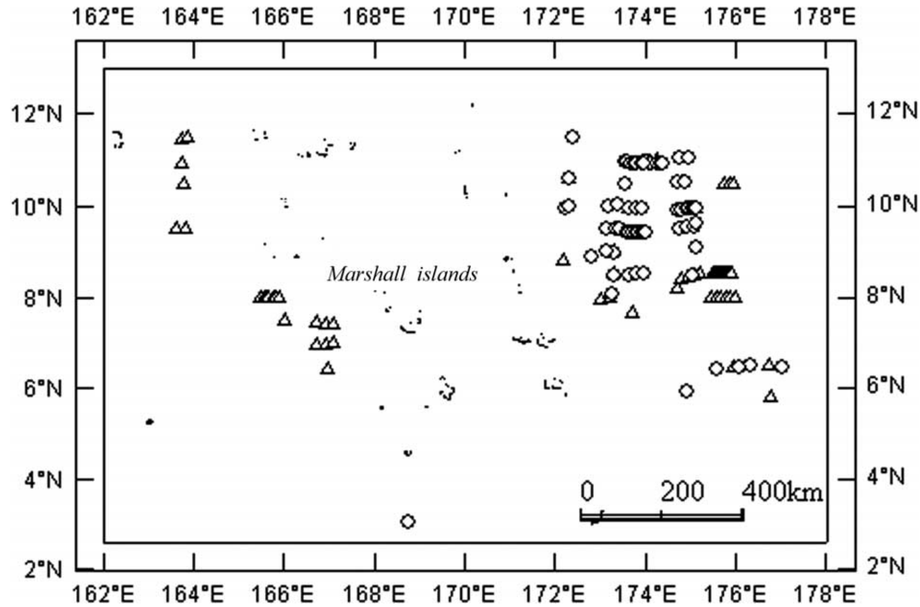

Figure 1 The hooked sites of bigeye thresher shark (◇: bigeye thresher shark; Δ: thresher shark).

360-mm-diameter hard plastic floats, 26 m of 5-mm-diameter long float lines and 20-m-long branch lines ending in either a ring hook or a circle hook. For the branch line, the first section was 3-mm-diameter polypropylene (1.5 m long), the second section was 1.8-mm-diameter nylon monofilament (18 m long), and the third section was 1.2-mm-diameter stainless wire (0.5 m long).

Two sets of fishing gear were used in the study, conventional and experimental gear. The designs of conventional and experimental gear are shown in Fig. A1 of the Appendix. The conventional gear configuration was used as the control to enable comparisons with previous studies and with the experimental gear used in this study. The conventional gear was assembled as one type of gear with no messenger weight (Table 1 for gear configurations). The experimental gears consisted of 16 types of gear with four groups of messenger weight (1.0, 1.5, 2.0 and 2.5 kg in water; Table 1).

The starting time of gear deployment was between 05:30 and 09:30 h local time, and fishing lasted about 4 h. The gear was retrieved between 16:00 and 22:00 h. The total operation usually lasted 10–11 h. During gear deployment, the vessel's speed was 4.0–4.75 m/s; line shooter speed was 5.0–5.75 m/s and the time interval between deploying consecutive branch lines was about 8 s. There were 25 hooks between successive floats (HBF). The vessel used about 1536 hooks per day (1000 ring hooks, 336 experimental ring hooks and 200 circle hooks). The ring hook was the conventional Japanese tuna hook (3.2 inch, i.e. standard Japanese hook size), being 46 mm long and 23 mm wide. One hundred circle hooks were used, to mitigate the bycatch of the sea turtles. The sizes of circle hook were 15/0 and 17/0 (see Yokota et al. 2006 and Ward & Hindmarsh 2007 for images of circles hooks). During deployment, the first part of the longline was conventional gear (about 200 ring hooks), the second part was experimental gears (about 336 ring hooks), the third part was 15/0 and 17/0 circle hooks (about 100 each), and the last part was again conventional gear (about

Table 1 The configuration of conventional and experimental gears.

Gear	Type no.	Weight of lead sinker (g)	Weight of leaden barrel swivel (g)	Messenger weight (kg)	Luminous sleeve
Conventional	1	/	6	/	/
Experimental	1	75	75	1.0	Yes
	2	75	60	2.0	Yes
	3	75	38	2.5	No
	4	75	75	1.5	No
	5	37.5	75	2.5	No
	6	37.5	60	1.0	No
	7	37.5	38	1.5	Yes
	8	37.5	75	2.0	Yes
	9	18.75	75	1.5	Yes
	10	18.75	60	2.5	Yes
	11	18.75	38	2.0	No
	12	18.75	75	1.0	No
	13	11.25	75	2.0	No
	14	11.25	60	1.5	No
	15	11.25	38	1.0	Yes
	16	11.25	75	2.5	Yes

800 ring hooks). The baits were Pacific saury (*Cololabis saira*), squid (*Loligo* spp.) and round scad mackerel (*Decapterus macrosoma*). The arrangement of the baits between two floats was three Pacific saury, three squid, 13 (or nine for the experimental gears) round scad mackerel, three squid and three Pacific saury.

Environmental monitoring

Depth, temperature, salinity and dissolved oxygen were sampled using a Submersible Data Logger XR-620 and TDR (2050) (RBR Co., Halifax, Canada; the survey vessel was equipped with nine TDRs). These environmental variables were measured at 69 sites using the XR-620 or TDR2050 after the gear was deployed. The variables measured at one site were applied to entire area where the mainline (about 100 km long) was deployed in one operation. Water temperature, salinity and dissolved oxygen vertical profiles changed with latitude over the study area and are shown in Fig. 2. The maximum water depth for which environmental variables were measured was about 450 m.

The following data were also collected: deployment position and time, duration of retrieving lines, number of hooks, code of hook with which a shark was caught, number of hooked bigeye thresher shark and thresher shark per day, and hooking position of bigeye thresher shark and thresher shark.

The measurement ranges of the environmental variables and the precision of the data are as in Song et al. (2009). Owing instrument accuracy and the requirements of the study, the data for depth and temperature were processed to one effective decimal place, salinity, dissolved oxygen and catch rate to two decimal places.

Relationship between actual and theoretical hook depths

The development of hook depth models is detailed in the Appendix.

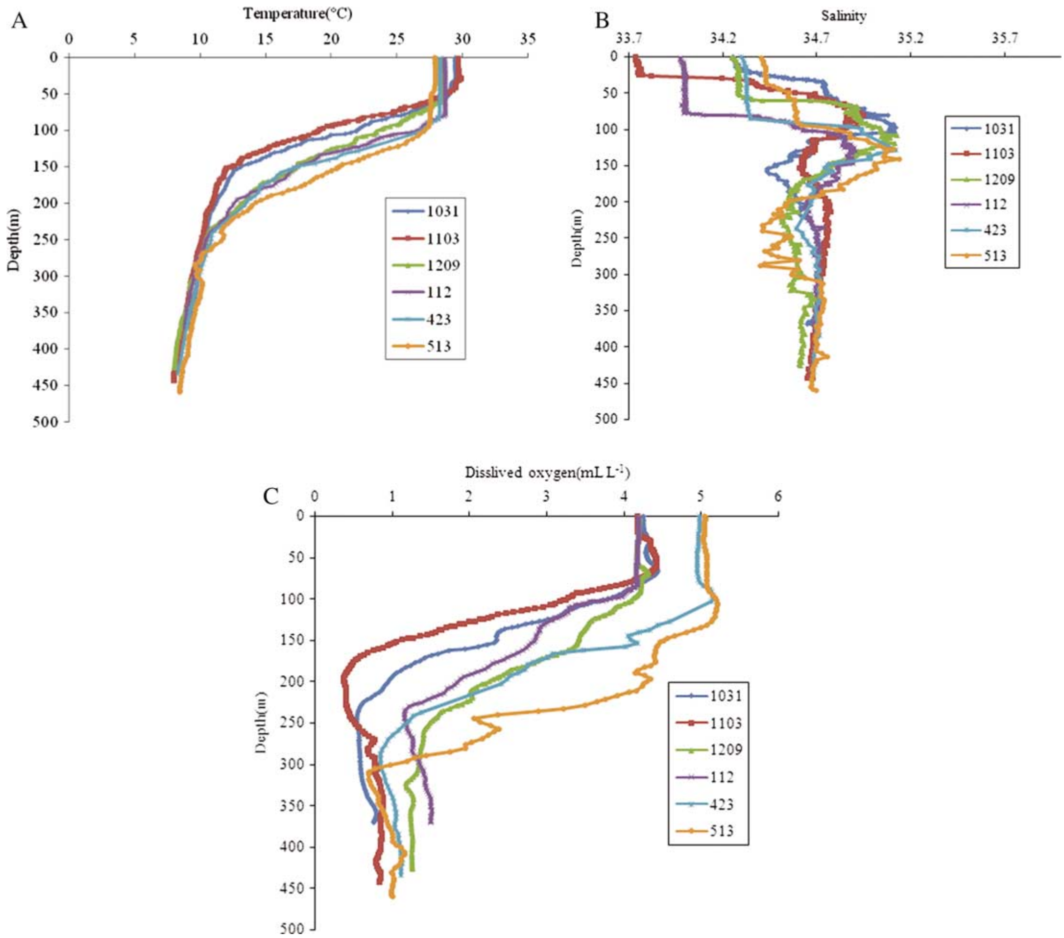

Figure 2 **A**, water temperature **B**, salinity and **C** dissolved oxygen, vertical profiles changed with latitudes over the study area (1031: 31 Oct. 2006, 9°33′N, 175°56′E; 1103: 3 Nov. 2006, 8°01′N, 175°58′E; 1209: 9 Dec. 2006, 10°58′N, 164°03′E; 112: 12 Jan. 2007, 5°58′N, 166°27′E; 423: 23 Apr. 2007, 8°34′N, 173°30′E; 513: 13 May 2007, 10°33′N, 175°01′E).

The depth, temperature, salinity and dissolved oxygen of hooked fish

The catch data from this survey and three hook types were pooled. The catch rates (CPUEs) of bigeye thresher shark and thresher shark in various classes of depth, temperature, salinity and dissolved oxygen were used to analyse the sharks' habitat (swimming depth, temperature, salinity and dissolved oxygen) (Table 2, Fig. 3). Catch rates of the study species for the various classes of environmental variables were

Table 2 Classes of depth, temperature, salinity, and dissolved oxygen for the hooked sharks with 'interval' of observation.

Environmental variables	Starting point	Final point	Interval	Total classes
Depth (m)	40.0	359.9	40	8
Temperature (°C)	8.0	29.9	2	11
Salinity	34.30	35.29	0.1	10
Dissolved Oxygen (ml/l)	0.0	5.99	0.5	11

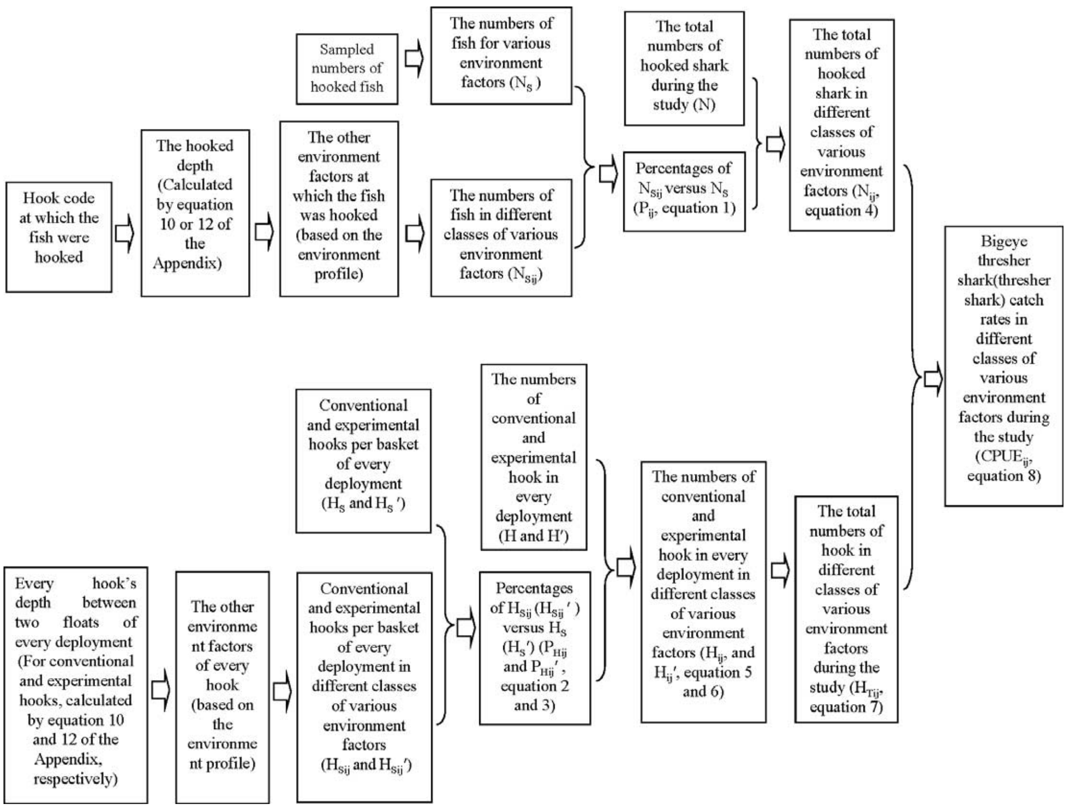

Figure 3 The diagram of data processing procedures. N_{Sij}, H_{Sij} and H_{Sij}' are calculated using the frequency statistic method. $_s$ indicates sample and $_i$ indicates various environmental variables. For example, "depth ($_i = 1$)" or "water temperature ($_i = 2$)" or "salinity ($_i = 3$)" or "chlorophyll-a ($_i = 4$)" or "dissolved oxygen ($_i = 5$)". $_j$ is the ranges of various environmental variables (see Tab. 2)

estimated by the following equations (Song et al. 2008, 2009).

$$P_{ij} = N_{Sij} / N_S \tag{1}$$

$$P_{Hij} = H_{Sij} / H_S \tag{2}$$

$$P'_{Hij} = H'_{Sij} / H_S' \tag{3}$$

$$N_{ij} = P_{ij} \times N \tag{4}$$

$$H_{ij} = P_{Hij} \times H \tag{5}$$

$$H'_{ij} = P'_{Hij} \times H' \tag{6}$$

$$H_{Tij} = \sum_{\xi=1}^{n} H_{ij} + \sum_{\xi=1}^{m} H'_{ij} \tag{7}$$

$$CPUE_{ij} = N_{ij} / H_{Tij} \tag{8}$$

where ξ is the number of fishing days ($n =$ conventional fishing gear, $m =$ experimental gear); $i = 1,2,3,4$; j has different values for depth ($j = 1,2,3,4, \ldots 8$), water temperature ($j = 1,2,3,4, \ldots 11$), salinity ($j = 1,2,3,4, \ldots 10$) and dissolved oxygen ($j = 1,2,3,4, \ldots 11$).

We used hierarchical cluster analysis (Tang & Feng 2002) to determine whether data in each class of depth, temperature, salinity and dissolved oxygen were correlated with catch rate (calculated in Equation 8), number of hooked bigeye thresher shark and thresher shark (calculated in Equation 4) and hooks (calculated in Equation 7), and if so, how. Euclidean distance was used in the cluster analysis, which was conducted following

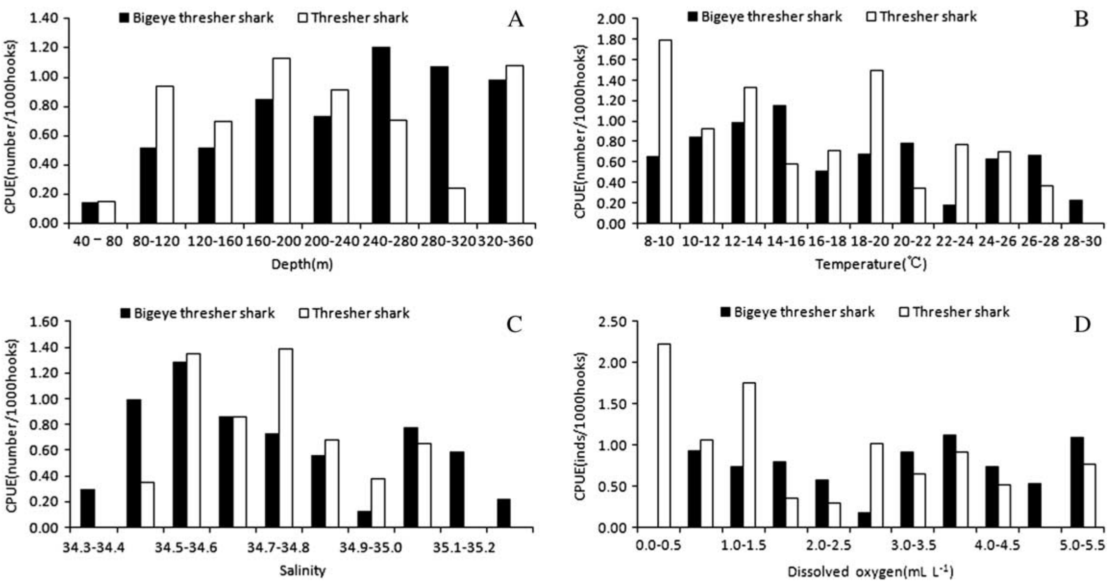

Figure 4 Bigeye thresher shark and thresher shark CPUE (number per 1000 hooks) at different classes of **A**, depth **B**, temperature **C**, salinity and **D**, dissolved oxygen.

Ward's method by using DPS software (Tang & Feng 2002). The data were standardised to a mean of zero and a standard deviation of one before the cluster analysis.

Results

Bigeye thresher shark and thresher shark catch rates

The catch rates of bigeye thresher shark and thresher shark at various depth, temperature, salinity and dissolved oxygen ranges are shown in Fig. 4(A–D). The depths at which the bigeye thresher shark and thresher shark were caught were 80–320 and 80–360 m, temperature 8–30 and 8–28°C, salinity 34.3–35.3 and 34.4–35.1, and dissolved oxygen 0.5–5.5 and 0–4.5 ml/l, respectively. Catch rates of bigeye thresher shark and thresher shark were at 240–280 and 160–200 m in depth (Fig. 4A), 14–16 and 8–10°C (temperature; Fig. 4B), 34.5–34.6 and 34.7–34.8 (salinity; Fig. 4C), 3.5–4.0 and 0–0.5 ml/l (dissolved oxygen; Fig. 4D), and the corresponding catch rates were 1.20 and 1.13, 1.15 and 1.79, 1.29 and 1.39, 1.12 and 2.22 sharks per 1000 hooks, respectively.

The relationship between sharks and environmental variables

The relationship between bigeye thresher shark and thresher shark populations, catch rates, hooks and various environmental variables are shown in Figs. 5 and 6, and Tables 3 and 4, respectively. From Table 3, it can be seen that the optimum swimming depths for bigeye thresher sharks are 240–360 m, temperature 10–16°C, salinity 34.5–34.7, and dissolved oxygen 1.0–2.0, 3.0–4.0, 5.0–5.5 ml/l. Similarly, from Table 4, the optimum environmental conditions for thresher sharks are 160–240 m water depth, 8–10, 18–20°C water temperature, 34.5–34.8 salinity, and 0.0–0.5, 1.0–1.5 ml/l oxygen level.

Discussion

The habitat of bigeye thresher shark and thresher shark

As seen in Fig. 2, the temperature and salinity of the seawater were higher, and the dissolved oxygen was lower in October and November of 2006. However, the temperature and salinity of

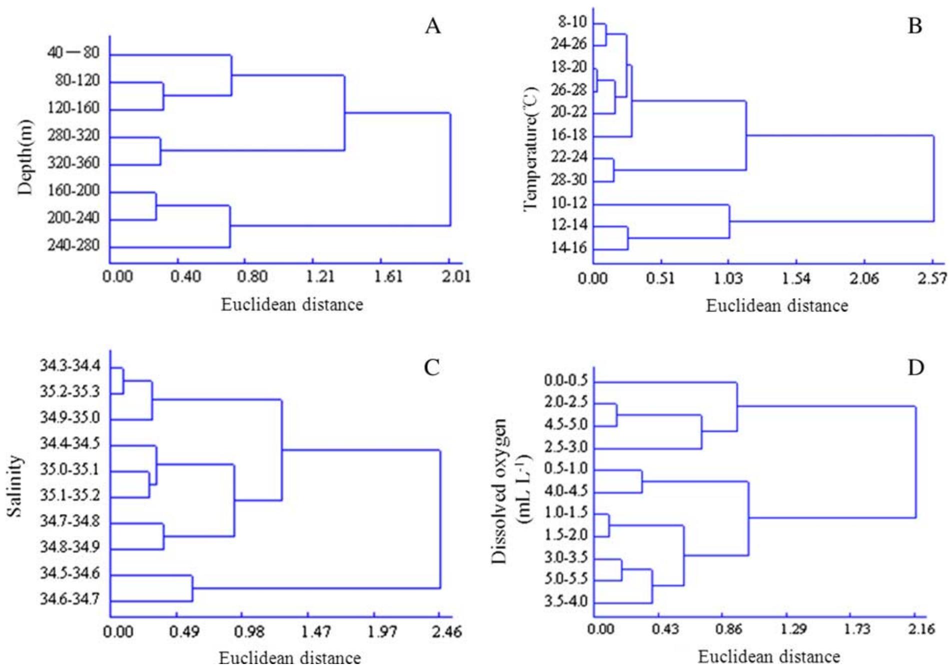

Figure 5 Results of cluster analyses of individuals, CPUE of Bigeye thresher shark, hooks, and classes of **A**, depth **B**, temperature **C**, salinity and **D** dissolved oxygen.

the seawater were lower, and the dissolved oxygen was higher, in April and May of 2007. Moreover, bigeye thresher sharks were mainly caught in April and May of 2007, while thresher sharks were mainly caught in November and December of 2006. Vertical profiles of the various environmental variables (Fig. 2) indicated that the main catch periods coincided with optimum conditions for bigeye thresher sharks and thresher sharks. The highest catch rate of thresher shark was when the temperature was 8–10°C and dissolved oxygen was 0.0–0.5 ml/l, but the number of hooks and hooked sharks were too few in these two classes for in-depth analysis (there was a larger sampling error in those classes with highest catch rate).

Other studies

The results of this study are presented with those of other studies in Table 5. In our study, we did not catch any bigeye thresher shark in depths greater than 360 m or less than 40 m. Therefore, that species' distribution in those water layers is not clear. However, between 40 and 360 m, the optimum water layer, water temperature and salinity of bigeye thresher shark was 240–360 m, 10–16°C and 34.5–34.7, respectively. In this study, the time when the bigeye thresher shark was hooked was unknown: some sharks might have been caught as they ascended, entering shallow depths, or as they descended to deep waters. The results of this study are different from those of Liu (2007) and Weng & Block (2004). Liu (2007) used theoretical hook depths to analyse shark habitat without considering environmental factors, such as ocean currents, which might make hooks 'shoal', and that study's sampling depth was shallower than that of this study. The results of this study reflected the bigeye thresher shark and thresher shark's catchability by longline gears.

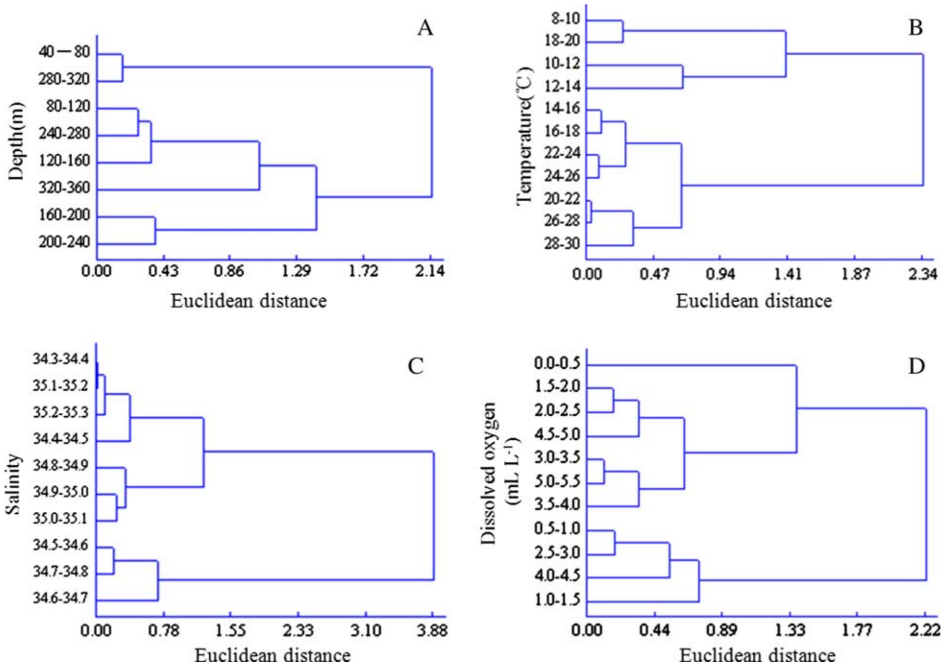

Figure 6 Results of cluster analyses of individuals, CPUE of thresher shark, hooks, and classes of **A**, depth **B**, temperature **C**, salinity and **D**, dissolved oxygen.

There are a few studies on the habitat and biology of thresher shark (FAO 2002). The thresher sharks are often distributed in coastal waters over the continental and insular shelves, and in the epipelagic layer far from land, in temperate to tropical waters. The young often inhabit the nearshore and inshore waters, and shallow bays. The swimming depth range of thresher shark reported in FAO (of 0–366 m; 2002) is consistent with the results of this study.

Comparisons of bigeye thresher shark and thresher shark habitat

Based on the optimum swimming depth, water temperature, salinity and dissolved oxygen ranges of bigeye thresher sharks and thresher sharks (Table 5), the swimming depth of bigeye thresher sharks was deeper than that of the thresher shark during the daytime. The bigeye thresher shark was more capable of tolerating lower temperatures, but the two species had almost the same optimum salinity. They can be widely distributed in the areas where the dissolved oxygen is higher than 0.5 ml/l, but the thresher shark can tolerate lower dissolved oxygen ranges than can the bigeye thresher shark.

The preferred habitat of the same shark species in different areas

The environment of a shark's environment may be influenced by currents, seabed topography and distribution of food organisms, among other factors. The same shark species prefers different habitats in different areas (Weng & Block 2004; Sims et al. 2005). For example, in the Gulf of Mexico, the bigeye thresher shark spends the majority of the daytime below the thermocline between 300 and 500 m, and most of the night in the mixed layer and upper thermocline between 10 m and 100 m. However, in Hawaiian waters, the night-time swimming depth of sharks was between 10 and 50 m,

Table 3 The correlations between specific class of environmental variables and the hooks, individuals and catch per unit effort (CPUE; number/1000 hooks) of bigeye thresher shark.

Environmental variable	Clustering	Class	Hooks	Individuals	CPUE
Depth (m)	The first	40–80	8063.20	1.10	0.14
	The second	80–120 120–160	31,962.73	16.48	0.52
	The third	280–320 320–360	6231.85	6.59	1.06
	The fourth	160–200 200–240	47,065.61	37.35	0.79
	The fifth	240–280	13,695.62	16.48	1.20
Temperature (°C)	The first	8–10 24–26 18–20 26–28 20–22 16–18	37,318.34	24.17	0.65
	The second	22–24 28–30	32,819.53	18.68	0.57
	The third	10–12 12–14 14–16	53,833.97	50.54	0.94
Salinity	The first	34.3–34.4 35.2–35.3 34.9–35.0	19,377.06	3.54	0.18
	The second	34.4–34.5 35.0–35.1 35.1–35.2	15,302.11	11.82	0.77
	The third	34.7–34.8 34.8–34.9	30,617.99	20.10	0.66
	The fourth	34.5–34.6 34.6–34.7	41,721.85	42.55	1.02
Dissolved oxygen (ml/l)	The first	0.0–0.5	1702.51	0.00	0.00
	The second	2.0–2.5 4.5–5.0 2.5–3.0	28,983.95	10.80	0.37
	The third	0.5–1.0 4.0–4.5	30,185.56	25.20	0.83
	The fourth	1.0–1.5 1.5–2.0 3.0–3.5 5.0–5.5 3.5–4.0	46,146.98	42.00	0.91

whereas its daytime swimming depth was between 400 and 500 m (Weng & Block 2004). Specifically, the bigeye thresher shark spent night-time above the thermocline and daytime below it (Weng & Block 2004). The basking shark exhibited a normal dusk ascent–dawn

Table 4 The correlations between specific class of environmental variables and the hooks, individuals of thresher shark and catch per unit effort (CPUE; number/1000 hooks) of thresher shark.

Environmental variable	Clustering	Class	Hooks	Individuals	CPUE
Depth (m)	The first	40–80 280–320	13,172.63	2.42	0.18
	The second	80–120 240–280 120–160 320–360	46,780.75	36.25	0.77
	The third	160–200 200–240	47,065.61	48.33	1.03
Temperature (°C)	The first	8–10 18–20	9866.79	15.71	1.59
	The second	10–12	28,787.61	26.58	0.92
	The third	12–14	14,582.41	19.33	1.33
	The fourth	14–16 16–18 22–24 24–26	30,526.95	20.54	0.67
	The fifth	20–22 26–28 28–30	23,255.24	4.83	0.21
Salinity	The first	34.3–34.4 35.1–35.2 35.2–35.3 34.4–34.5	17,196.85	1.24	0.07
	The second	34.8–34.9 34.9–35.0 35.0–35.1	30,226.33	17.40	0.58
	The third	34.5–34.6 34.7–34.8 34.6–34.7	59,595.82	68.36	1.15
Dissolved oxygen (ml/l)	The first	0.0–0.5	1702.51	3.78	2.22
	The second	1.5–2.0 2.0–2.5 4.5–5.0	25,767.61	6.3	0.24
	The third	3.0–3.5 5.0–5.5 3.5–4.0	24,083.53	18.91	0.79
	The fourth	0.5–1.0 2.5–3.0 4.0–4.5	43,927.78	37.83	0.78
	The fifth	1.0–1.5	11,534.57	20.17	1.75

descent swimming pattern when occupying the deep water of fjord-like Clyde Sea and when on the edge of the European shelf, whereas it showed a dusk descent–dawn ascent swimming pattern in the inner-shelf areas of the western English Channel (Sims et al. 2005).

Table 5 Comparisons of the optimum class of various environment variables between this study and the other studies on bigeye thresher shark and thresher shark.

	In this study		In other studies				
Items	Bigeye thresher shark	Thresher shark	Authors	Species	Relatively high catch rate or concentration range	Data source	Study area
Depth (m)	240–360	160–240	Nakano et al. (2003)	Bigeye thresher shark	80–130 (at night); 200–500 (daytime)	Acoustic telemetry	Eastern Pacific Ocean
			Weng & Block (2004)	Bigeye thresher shark	10–100 (at night); 400–500 (daytime)	Pop-up satellite archival tag	Hawaii waters
					10–100 (at night); 300–500 (daytime)		Gulf of Mexico
			Liu (2007)	Bigeye thresher shark	230–290	Fishery survey data	Tropical Pacific Ocean
			FAO (2002)	Thresher shark	0–366	Unknown	Unknown
Temperature (°C)	10–16	18–20	Weng & Block (2004)	Bigeye thresher shark	24–26 (at night); 6–10 (daytime)	Pop-up satellite archival tag	Hawaii waters
					20–24 (at night); 6–12 (daytime)		Gulf of Mexico
			Liu (2007)	Bigeye thresher shark	11.5–13.5	Fishery survey data	Tropical Pacific Ocean
Salinity	34.5–34.7	34.5–34.8	Liu (2007)	Bigeye thresher shark	34.8–35.0	Fishery survey data	Tropical Pacific Ocean
Dissolved oxygen (ml/l)	3.0–4.0	1.0–1.5	Unknown	Unknown	Unknown	Unknown	Unknown

Implications for the conservation and CPUE standardisation

For the conservation of bigeye thresher shark and thresher shark, the following mitigation measures are suggested:

(1) Avoiding fishing in the peak areas and periods of shark abundance within Marshall Islands' EEZ: 8–11°N, 172–176°E, from April to May for bigeye thresher shark, and 9–12°N, 163–165°E and 6–8°N, 165–168°E, from November to December for thresher shark;
(2) Using fish instead of squid as bait (Bolten & Bjorndal 2002, 2003; Watson et al. 2005; Gilman et al. 2008);
(3) Using nylon monofilament leaders instead of wire leaders (Yokota et al. 2006; Ward et al. 2007; Gilman et al. 2008; Ward et al. 2008);
(4) Avoiding setting the baited hooks below 160 m, to reduce the bycatch of bigeye thresher shark and thresher shark, during the daytime. Unfortunately, it is very difficult for the fisher to implement this measure because the bigeye tuna's optimum water depth class was below 160 m (Holland et al. 1990; Boggs 1992; Holland et al. 1992; Mohri & Nishida 1999; Schaefer & Fuller 2002; Musyl et al. 2003; Song et al. 2009).

More research is needed to improve the effectiveness of the mitigation measures implemented for the bigeye thresher shark and thresher shark.

There are few regional fishery management organisations to conduct shark stock assessments: the International Commission for the Conservation of Atlantic Tunas, for blue and shortfin mako sharks in the North and South Atlantic (Gilman et al. 2008); and National Oceanic and Atmospheric Administration, for blue shark in the North Pacific Ocean (Kleiber et al. 2009). While scientists conduct shark stock assessments, we suggest the use of a 'habitat model' (Hinton & Nakano 1996; Biglow et al. 2002, 2003; Hinton & Maunder 2003) to standardise shark CPUE. In addition, the hook depth data could be input of the 'habitat model' because the depths at which fish are hooked are influenced by all environmental variables (Song et al. 2009).

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Appendix

Two sets of fishing gear, conventional and experimental gear, and two hook types, ring hook and circle hook, were used in the study. The following data were collected during the study to build the hook depth prediction models: vessel's course and speed, line shooter speed, number of HBF, time interval between two hooks. The TDRs were also used to measure the actual hook depth. The theoretical hook depths were calculated by the catenary curve equation (Saito 1992), assuming that the shape of conventional gear and experimental gear was as shown in Fig. A1.

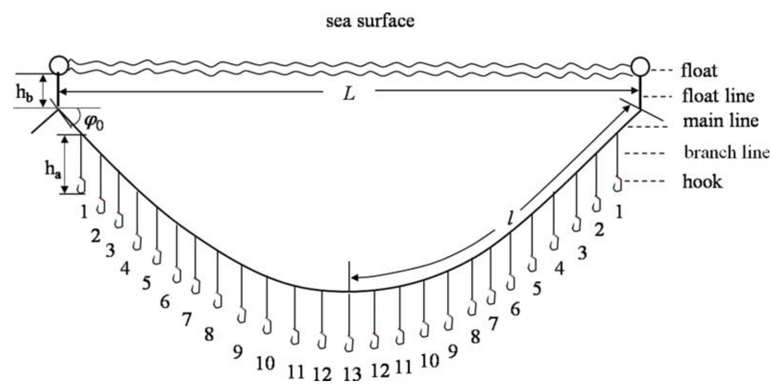

Figure A1 The figuration of traditional fishing gear under the water.

For the conventional gear, the catenary curve equations (Saito 1992) are used to calculate the hook depths.

$$D_j = h_a + h_b + l\left[\sqrt{1+\cot^2\varphi_0} - \sqrt{\left(1-\frac{2j}{n}\right)^2 + \cot^2\varphi_0}\right] \tag{A1}$$

$$L = V_2 \times n \times t \tag{A2}$$

$$l = {V_1 \times n \times t}/{2} \tag{A3}$$

$$k = L/2l = V_2/V_1 = \cot\varphi_0 sh^{-1}(\mathrm{tg}\varphi_0) \tag{A4}$$

where D_j is the theoretical hook depth of the conventional gear; h_a is the length of branch line (m); h_b is the length of float line (m); l is a half of the length of mainline between two consecutive floats (m); φ_0 is the angle between the horizontal and the tangential line to the mainline (°). Because φ_0 is hard to measure at sea, it is often estimated by k; j is the code of hooks between two floats; n is the HBF + 1; L is the distance between two floats on the sea surface (m); V_2 is the speed of boat (m s^{-1}); t is the time interval between two hooks (s); V_1 is the line shooter speed (m s^{-1}).

For the experimental gear, the shape of the mainline under the water changed because of the messenger weight. In this survey, we did not measure the depths at which the messenger weights were connected to the mainline. We used the arithmetic mean of actual depth of corresponding weight measured in the Indian Ocean (Song 2008) as the depth of these connecting positions. The corresponding depths at the connecting positions were 54.0 m for the 1.0-kg weight, 59.7 m for the 1.5-kg weight, 65.0 m for the 2.0-kg weight, and 67.7 m for the 2.5-kg weight (Song 2008).

To calculate the hook depth of the experimental gear, we made the following assumptions: (1) that the sunken depth of one type of messenger weights was constant during the survey; (2) that the mainline between position C and position D (Fig. A2) was a catenary curve; (3) that the mainline between A and C, B and D was a straight line. Based on the depth of the C and D, we calculated the horizontal distance between A and C, B and D, then we calculated the horizontal distance between C and D, denoted as L', using the following equations:

$$D'_j = h_{\bar a} + h_{\bar b} + d_{\bar w} + l\left[\sqrt{1+\cot^2\varphi'_0} - \sqrt{\left(1-\frac{2j}{m}\right)^2 + \cot^2\varphi'_0}\right] \tag{A5}$$

$$L' = V_2(m+4)t - 2\sqrt{(2V_1 t)^2 - (d_w - h_b)^2} \tag{A6}$$

$$l = V_1 \times m \times t/_2 \tag{A7}$$

$$k' = L'/2l = \cot\varphi'_0 sh^{-1}(\mathrm{tg}\varphi'_0) \tag{A8}$$

where the D'_j is the hook depth (m); d_w is the depth at which the messenger weight was connected (m); φ'_0 is the angle between the horizontal line and the tangent of C or D (°) (Fig. A2); m is the HBF + 1; k' is the sagging rate; L' is the horizontal distance between C and D (m); the others are the same as in Equations (A1)–(A4).

The relationships between the measured and calculated hook depths and the environmental data were quantified by the use of stepwise regression method (Song & Gao 2006; Song et al. 2008, 2009) to estimate the depth of hooks. For the conventional fishing gear, it was assumed that the hook depth was influenced mainly by gear drift velocity (denoted as V_g) over the ground, wind speed (V_w; measured by anemometer), wind direction (C_w; measured by compass), the angle of attack (γ) between the prevailing course in deploying gear and drifting direction of the fishing gear, and the angle (Q_w) between wind direction and the prevailing course during gear deployment (Song & Gao 2006; Song

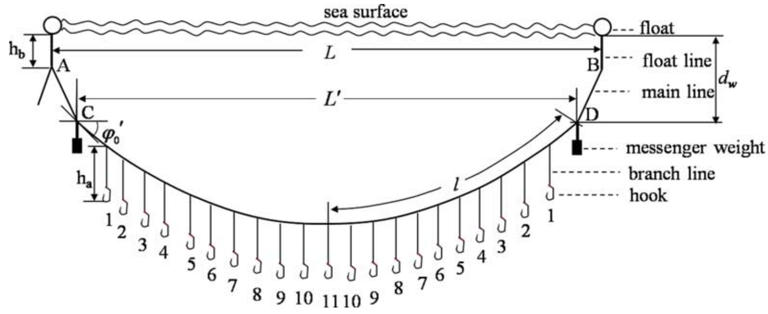

Figure A2 The figuration of experimental fishing gear under the water.

et al. 2008, 2009). The actual hook depths usually fluctuate continuously within a certain range (Song et al. 2008, 2009). For the experimental fishing gear, the weight of the messenger weight (W) in water was included as an additional factor in the model.

For the conventional fishing gear, we used following equation to fit the relationship between theoretical depths (D_j) and average hook depths measured by TDRs (D_f),

$$\lg(P) = a\lg(V_g) + b\lg(V_w) + c\lg(\sin Q_W) + d\lg(\sin\gamma) + e\lg(j) + C \tag{A9}$$

where P is the ratio of D_f and D_j, C is the constant; a, b, c, d and e are the respective parameters of variables. This regression model was fitted to the observed data, using the least-squares method. The resultant regression model was estimated as

$$D_{fj} = (V_g^{-0.218} \times j^{-0.107} \times V_w^{-0.251} \times 10^{-0.113}) \times D_j \tag{A10}$$

and $R = 0.72$, $n = 137$, $F = 145.46$ and $P < 0.0001$. The terms $\sin Q_W$ and $\sin\gamma$ are deleted because they were not significant. To predict the depths of hooks for the conventional fishing gear, we used Equation (A10) by inputting theoretical hook depth D_j, the environmental data V_g, V_w and hook code of j.

For the experimental fishing gear, we used following equation to fit the relationship between D'_j and average hook depths measured by TDRs (D'_f)

$$\lg(P') = a'\lg(V_g) + b'\lg(V_w) + c'\lg(\sin Q_W) + d'\lg(\sin\gamma) + e'\lg(j) + f'\lg(W) + C' \tag{A11}$$

where P' is the ratio of D'_f and D'_j, C' is the constant; a', b', c', d', e' and f' are the respective parameters of variables. This regression model was fitted to the observed data, using the least-squares method. The resultant regression model was estimated as

$$D'_{fj} = (V_g^{-0.196} \times j^{-0.135} \times V_w^{-0.208} \times 10^{-0.110}) \times D'_j \tag{A12}$$

and $R = 0.64$, $n = 413$, $F = 259.83$, and $P < 0.0001$. The terms $\sin Q_W$ and W are deleted because they were not significant. To predict the depths of hooks for the experimental fishing gear, we can use Equation (A12) by inputting theoretical hook depth D'_j, the environmental data V_g, V_w, $\sin\gamma$ and the hook code of j.