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An evaluation of differences in habitat quality between FADs-associated and unassociated schools of skipjack tuna Katsuwonus pelamis using quantile regressions

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An evaluation of differences in habitat quality between FADs-associated and unassociated schools of skipjack tuna *Katsuwonus pelamis* using quantile regressions

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Abstract: The use of drifting fish aggregation advices (FADs) by tuna purse seine fleets has greatly enhanced tuna catches since the 1990s. The large increase FAD use calls for studies to evaluate the potential ecological impacts on the entire life cycle of tunas, such as habitat selection, migration, feeding, growth and fitness. The effects of FADs on habitat selection of tunas are a research priority, since inappropriate habitat selection could alter life history traits. This study evaluated the quality of available habitat for free swimming schools and drifting-FAD-associated schools of skipjack tuna (*Katsuwonus pelamis*) in the western and central Pacific Ocean (WCPO). The habitat quality was quantified with an Integrated Habitat Index (*IHI*) that was developed using a quantile regression model based on available environmental variables. The free swimming schools tended to have higher *IHI* values compared to the FAD associated schools, suggesting that FADs draw skipjack tunas away from optimal habitats. The free swimming schools also had a wider variety of *IHI* values, suggesting that they encountered a broader range of habitats, compared to a more consistent FAD-driven habitat. These findings support the hypothesis that FADs may have potential impacts on habitat selection for fish associated with them. Additional environmental factors may be required within the Integrated Habitat Index model to more accurately quantify the habitat quality for FAD-associated and -unassociated schools in the further studies.

Key words: purse seine, skipjack tuna *Katsuwonus pelamis*, drifting fish aggregation devices, habitat selection, Integrated Habitat Index

Introduction

Tropical tunas and other pelagic fishes are often attracted to floating objects, forming aggregations under or around them (Bromhead et al., 2000). Tuna purse seine fisheries exploit this behavior by introducing fish aggregation devices (FADs), which have effectively increased the efficiency of tuna fishing operations. FAD sets have an approximated 90% success catch-rate compared with sets around free swimming schools, which succeed about 50% of the time (Sakagawa, 2000). Approximately 40% of the world's current total tropical tuna catch comes from purse seine sets on naturally formed and artificial floating objects (Dagorn et al., 2013). The increased application of FADs worldwide has left many unanswered questions regarding the impact on life histories and habitat choices of tunas (Marsac et al., 2000; Hallier and Gaertner, 2008; Dagorn et al., 2013). These unanswered questions lead to increased uncertainty in understanding tunas' population dynamics and developing FAD management strategies for sustainable fisheries.

Previous studies have evaluated the potential impacts of FADs on tuna biology in addition to the impacts on behavior patterns (Marsac et al., 2000; Ménard et al., 2000; Hallier and Gaertner, 2008). These studies have compared biological indicators of fish aggregating around the FADs to conspecifics in unassociated schools (i.e. free swimming schools). Concerns have been raised regarding altered feeding patterns (Ménard et al., 2000; Hallier and Gaertner, 2008; Jaquemet et al., 2011), reduced plumpness and growth rates (Marsac et al., 2000; Hallier and Gaertner, 2008), and changes in migration direction (Hallier and Gaertner, 2008) and pattern (Wang at al., 2014). These studies demonstrated that the presence of FADs may negatively affect tunas throughout their life history and inferred that reduced biological indicators of tuna associated with FADs are a result of poor habitat quality (Marsac et al., 2000; Hallier and Gaertner, 2008).

Commonly used biological indicators to measure fish well-being (condition) are assumed to reflect the environmental conditions (Blackwell et al., 2000). Various measures of fish condition (e.g. plumpness, lipid contents and feeding status) have been widely used in previous studies to infer the habitat conditions for

FAD-associated fish (Marsac et al., 2000; Hallier and Gaertner, 2008; Jaquemet et al., 2011; Robert et al., 2014). However, condition indices of a highly migratory species that have a long distance movement in the short period may not reflect the condition of habitat where they are captured. Thus, it is imperative to build upon these previous studies and quantitatively characterize the quality of habitat, as opposed to relying on condition indices to deduce that fish reside in poor habitat conditions.

Habitat modeling incorporates environmental variables that influence the spatial distribution of species abundance, either directly or indirectly, and can be used to predict the effects of changes in habitat conditions on fish's distribution patterns (Austin, 2002, 2007). The subsequent habitat suitability index (HSI) is estimated from the relative abundance of fish in a given area to quantify the quality of available habitat (Donovan et al., 1987; Gillenwater et al., 2006; Love, 2011).

The goal of this study is to quantify the quality of available habitat between free swimming schools and drifting-FAD-associated schools. Skipjack tuna (*Katsuwonus pelamis*) are used to evaluate the relative differences in habitat quality in associated and free swimming schools. Skipjack are a target species in purse seine fisheries, accounting for 75% and 63% of the global catch of tunas on free swimming and associated schools, respectively (Dagorn et al., 2013). The hypothesis that habitat quality is different for free swimming schools and associated schools is tested and examined through the development of a habitat suitability index model to quantify the habitat quality. This study aims to improve the understanding of potential impacts of FADs on habitat selection for skipjack tuna.

Materials and methods

Tuna purse seine observer survey data

Data were collected from three survey cruises by the Tuna Purse Seine Fishery Observer Program from 2007 to 2011 (Table 1). Tuna purse seiners, Pohnpei No.1, Jinhui No.6 and Jinhui No.7, caught skipjack tuna from both free swimming and associated schools in the western and central Pacific Ocean (WCPO, Fig.1). During the survey period, both free swimming single species (pure) as well as mixed species schools were observed and captured. Data for thirty-two free swimming schools were comprised of both pure and mixed schools of skipjack. Data for eighty-three associated schools were collected for seventy-nine aggregations associated with drifting FADs and four drifting FADs attached to randomly occurring debris (i.e., branches or iron buckets). Observers recorded a variety of data included date, sampling station position and total weight of catch (tonnes) for each set.

Table 1. The survey cruises, date, fishing days, number of total sets, number of successful sets.

Voyage	1		2		3	
Dates	10/2007-01/2008		10/2010-05/2011		10/2011-11/2011	
Fishing days	73		182		56	
School type	Free school	Associated school	Free school	Associated school	Free school	Associated school
The number of total sets	52	14	35	133	60	24
The number of successful sets	22	13	15	116	19	12
The number of observed sets	6	2	9	70	17	11

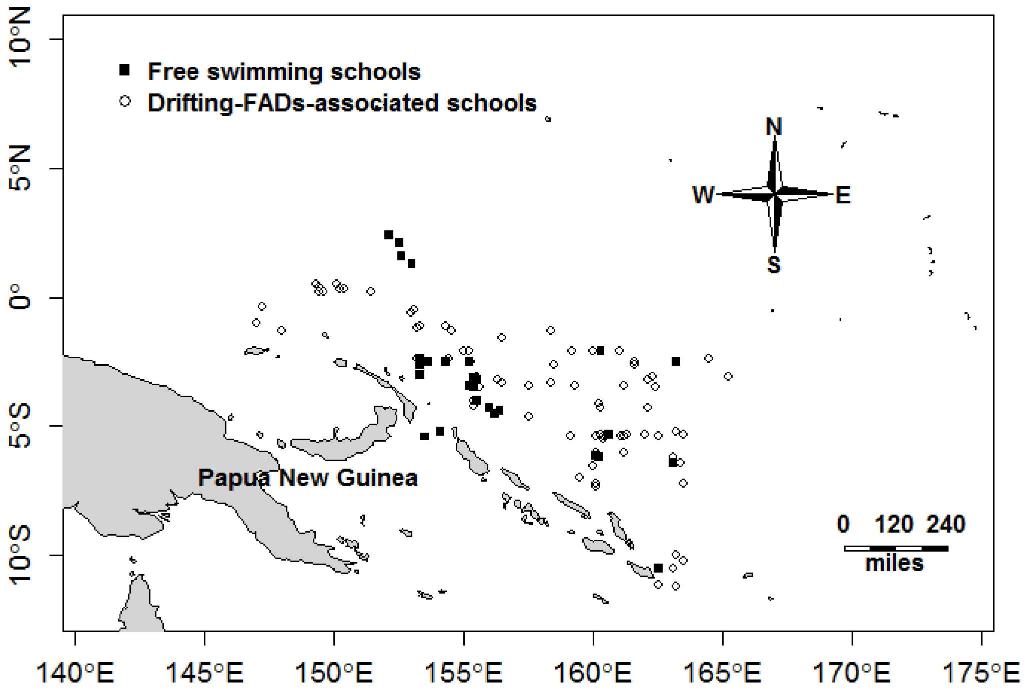

Fig.1. Location of sampling stations in the western and central Pacific Ocean.

Environmental data were recorded for all sets and included the sinking depth of fishing gear and corresponding temperatures. Water temperature was recorded by a Temperature and Depth Recorder (TDR-2050, RBR Ltd., Ottawa, Canada). Depth measurement error was within ± 0.05 % in depths of 10 to 740 m, and temperature was measured to ± 0.002 °C. The TDR was fixed to the center of the bottom line of the fishing gear where the maximum sinking depth of the purse seine could be recorded.

Comparison of habitat quality

Environmental and spatio-temporal variables

Temperature is a known factor limiting the spatial distribution and abundance of skipjack tuna that can affect the movement of tuna, either directly or indirectly (Sund et al., 1981; Senina et al., 2008). Temperature limits prey availability, which plays an important role in defining “favorable habitat” for tuna (Sund et al. 1981; Lebourges-Dhaussy et al. 2000). Empirical evidence suggests that change in sea surface temperature was a factor influencing tuna to leave FADs (Moreno et al., 2007).

Environmental conditions in the Warm-Pool of the WCPO are distinctly different from the conditions reported in the published literature from other locations (Leroy et al., 2009). FADs-associated skipjack tuna in the Warm-Pool of the WCPO were mostly distributed in depths shallower than 100 m (Matsumoto et al., 2006; Leroy et al., 2009). Thus the depths 0-100 m were considered the dominant vertical habitat of skipjack for this study. T_{40} and T_{100} were used to represent the vertical thermal habitat for skipjack tuna in their dominant habitat. T_{40} is the arithmetic mean of temperatures from 0 m to 40 m below the surface to represent shallow thermal habitats and T_{100} is the arithmetic mean of temperatures from 40 m to 100 m, representing the vertical deep water thermal habitats.

The structure of the thermocline is also thought to influence tuna distribution, with skipjack tuna preferentially inhabiting the upper limit (Barkley et al., 1978). To reflect this relationship, the depth of upper limit of the thermocline (D) (i.e., the thickness of the mixed layer, Green, 1967) was included in the model as an environmental variable. D was estimated using the sinking depth data and temperature recorded by the TDRs. The threshold standard of the thermocline was

$$\left|\Delta T / \Delta Z\right| = 0.05°\mathrm{C}m^{-1} \qquad (1)$$

where T is temperature and Z is depth. If the absolute value of vertical temperature gradient is higher than or equal to $0.05^{\circ}\mathrm{C}*\mathrm{m}^{-1}$, the water layer depth was defined as D (Song et al., 2008). The vertical temperature gradient was calculated as

$$G_z = (T_{z+1} - T_z) / (D_{z+1} - D_z) \qquad (2)$$

where T_Z and D_Z are the arithmetic average values of temperature and depth binned together in increments of 10 (i.e. 0-10m, 10-20m, 20-30m…etc.); G_Z is the vertical temperature gradient value between the standard depth D_Z and D_{Z+1}. For more details for calculating D see Song et al. (2008).

Latitude, longitude, year, and month were also included in the model to implicitly represent the spatio-temporal variability in environmental conditions and their impact on the distribution of fish (Austin, 2002).

Quantile Regression Model

The majority of models that link environmental variables with species distributions (e.g., GLM, GAM) are based on the estimation of mean or median (i.e., the central tendency) of species responses to environmental variables (Oksanen and Minchin, 2002). However, the central tendency modeling approach does not properly estimate limiting effects of the environment (Vaz et al., 2008). Quantile regression models have been increasingly used as a way to estimate a more complete range of species' responses to environmental gradients, with the highest quantile representing the species maximum abundance given ideal environmental conditions (Eastwood et al., 2003; Vaz et al., 2008; Song and Zhou, 2010). A quantile regression model was used to standardize skipjack abundance with respect to environmental variables. This model can be described as:

$$Log(B_i + 1) = \beta_0 + \beta_1 F + \beta_2 Y + \beta_3 M + \beta_4 Lat + \beta_5 Long + \beta_6 T_{40} + \beta_7 T_{100} + \beta_8 D + \varepsilon \qquad (3)$$

where B_i is the catch caught by a seiner at sampling station i, which represents the biomass of the aggregation and is assumed to be proportional to the abundance; $Log(B_i + 1)$ transformation is to reduce heteroscedasticity in the data and limit the effect of heterogeneous error distribution of the models (Cade and Richard, 2005); F is aggregation type (associated school = 1 and free swimming school = 2) with associated school as the reference level; Y is year (2007, 2008, 2010, 2011) with 2007 as the reference level; M is month (January, February, March, April, May, October, November, December) with January as the reference level; Lat is latitude; $Long$ is longitude; T_{40} is the temperature mean from 0-40 m; T_{100} is the temperature mean from 40-100 m; D is the upper depth of the thermocline; β_0 is the intercept; β_i, i = 1, 2, 3, 4, 5, 6, 7, 8 are unknown parameters to be estimated; and ε is an error term.

Starting with the full model, single terms were removed by backward elimination based on average P-values at five quantile intervals from the highest quantile (95th) to the lowest (10th). Insignificant variables ($p > 0.05$) were removed after each iteration and the reduced model was re-run across all 5 quantiles. Significance tests were again performed to eliminate additional variables according to the same rule until a parsimonious model ($p < 0.05$) was identified in at least one quantile. The highest quantile was chosen as the area with the highest abundance in cases where the resulting model was found to have all variables significant in more than one quantile. More information about quantile choice and model selection can be found in Vaz *et al.* (2008). The optimal quantile regression model was used to predict species abundance to quantify habitat quality at each sampling location.

Quantification of habitat preference

An Integrated Habitat Index (*IHI*) was used to overcome the disadvantages of traditional *HSI* models based on methods described by Song and Zhou (2010). In traditional *HSIs,* the weight of each environmental variable must be chosen based on expert opinion. Additionally, a normal distribution is required for most *HSIs* (Song and Zhou, 2010). The *IHI* for free swimming and associated schools were calculated with the following equation

$$IHI_i = B_i / B_{max} \tag{4}$$

where B_i is the standardized abundance index at sampling station i and B_{max} is the maximum value of all B_i (Song and Zhou, 2010). A sampling location with an *IHI* value closer to one implies that the environment of the station is more suitable for skipjack.

Portions of *IHI,* the average *IHI* value, variance, and the 95% bootstrapped confidence intervals (CIs) were estimated for free swimming and associated schools. Bootstrapped CIs were estimated by re-sampling the original data n times (n = number of original *IHI* values) with replacement for 1000 iterations to calculate.

Results

The significance test of the coefficients in the selected model showed that the quantile regression models corresponding to the 45th and 50th quantiles were both suitable. However, the quantile regression model corresponding to the 50th quantile was determined to best fit the relationship between abundance index and the environmental variables as the higher quantile, based on the selection rules described in the methods. The optimal model determined temperature (T_{100}), latitude and longitude to be the significant variables describing skipjack tuna habitat (Table 2).

Table 2. Estimates of the model parameters for the quantile regression model with 50th quantile used to standardize the biomass of skipjack aggregations with respect to environmental variables. The fitted parameters were the mean of temperature in the depth from 40-100 m (T_{40}), latitude (*Lat*), and longitude (*Long*). Significance code were *** ($P < 0.001$), ** ($P < 0.01$) and * ($P < 0.05$).

Variable	Estimate	Standard error	t value	Pr (>|t|)	Significance code
Intercept	-25.05768	7.90131	-3.17597	0.00196	**
T_{100}	0.52855	0.12142	4.35314	0.00003	***
Lat	0.12759	0.0505	2.52625	0.01294	*
Long	0.08174	0.03788	2.15796	0.03309	*

The residual-fit plot indicated (Fig. 2A) that the spread of the residual values was small, relative to the spread of the fitted values, and the q-q plot (Fig. 2B) indicated that the residual distribution was normally distributed.

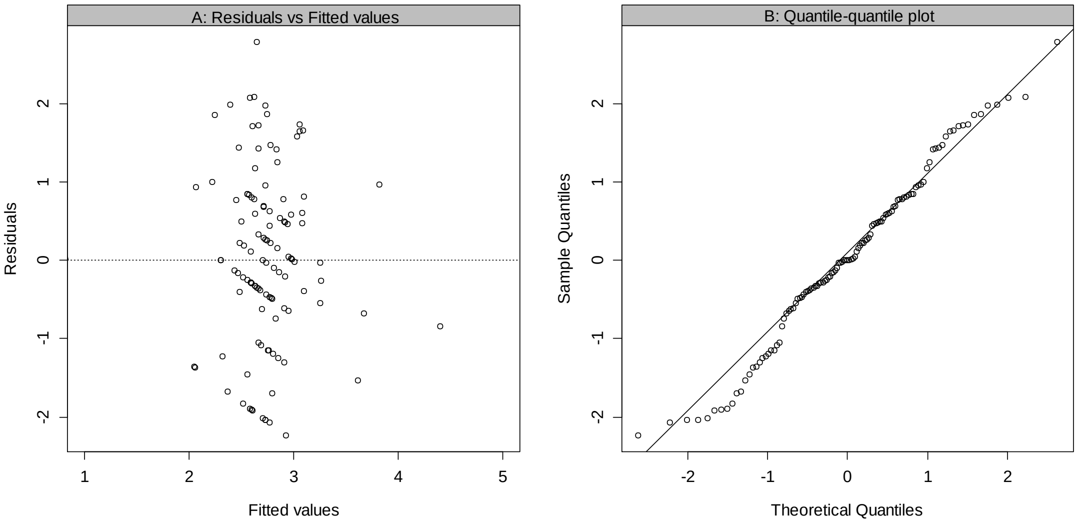

Fig.2. Residual plots (A) for the regression quantile model and (B) Quantile-Quantile plot

The range of *IHIs* for free swimming schools and associated schools was from 0.1134 to 1.0000 and 0.0245 to 0.3194, respectively. Figure 3 displayed the spatial distribution of 32 *IHIs* for free swimming schools and 83 *IHIs* for associated schools. It was easily observed that there were some much higher *IHIs* in free swimming schools (Fig.3).

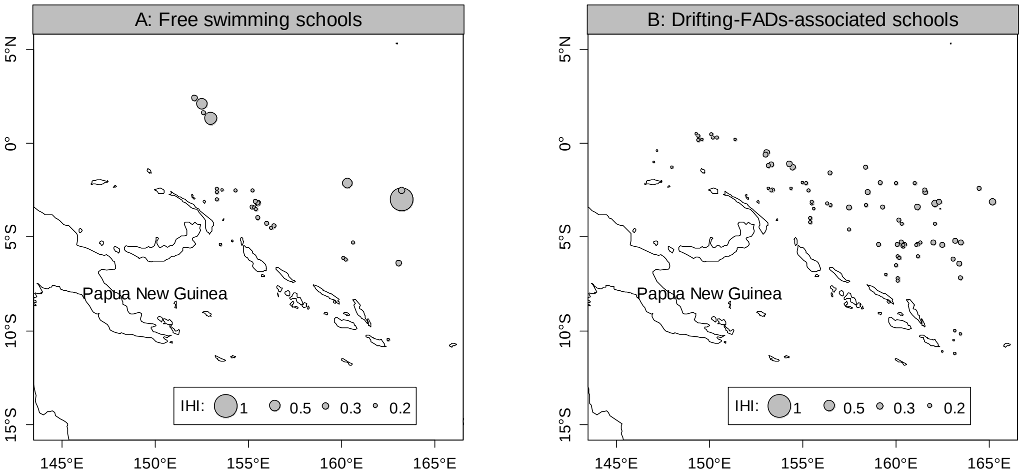

Fig.3. Integrated habitat indices (*IHI*) for each station for skipjack associated with drifting fish aggregation devices (FADs) and caught on free swimming schools.

The range of *IHIs* was divided into the sections, 0-0.15, 0.15-0.3 and 0.3-1.0. The reason for disproportionate partitioning from 0.3-1.0 is that there were too few data for additional partitioning. For 32 *IHIs* for free swimming school, portions of these three sections were 12.50%, 71.88% and 15.63%, the 1000 bootstrapped 95% CIs of the corresponding portions were [3.13%, 25.00%], [56.25%, 87.50%] and [3.13%, 28.13%], respectively. In contrast, section portions of 83 *IHIs* of associated schools were 16.87%, 80.72% and 2.41%, and their 95% CIs were [9.64%, 25.3%], [72.29%, 89.16%] and [0.00%, 6.02%], respectively (Fig. 4). Figure 4 indicated that there were similar portion compositions in the lower *IHIs* sections 0-0.15 and 0.15-0.3 for two types of schools, but the portion of the *IHIs* more than 0.3 for free swimming school was significantly higher than that for associated schools.

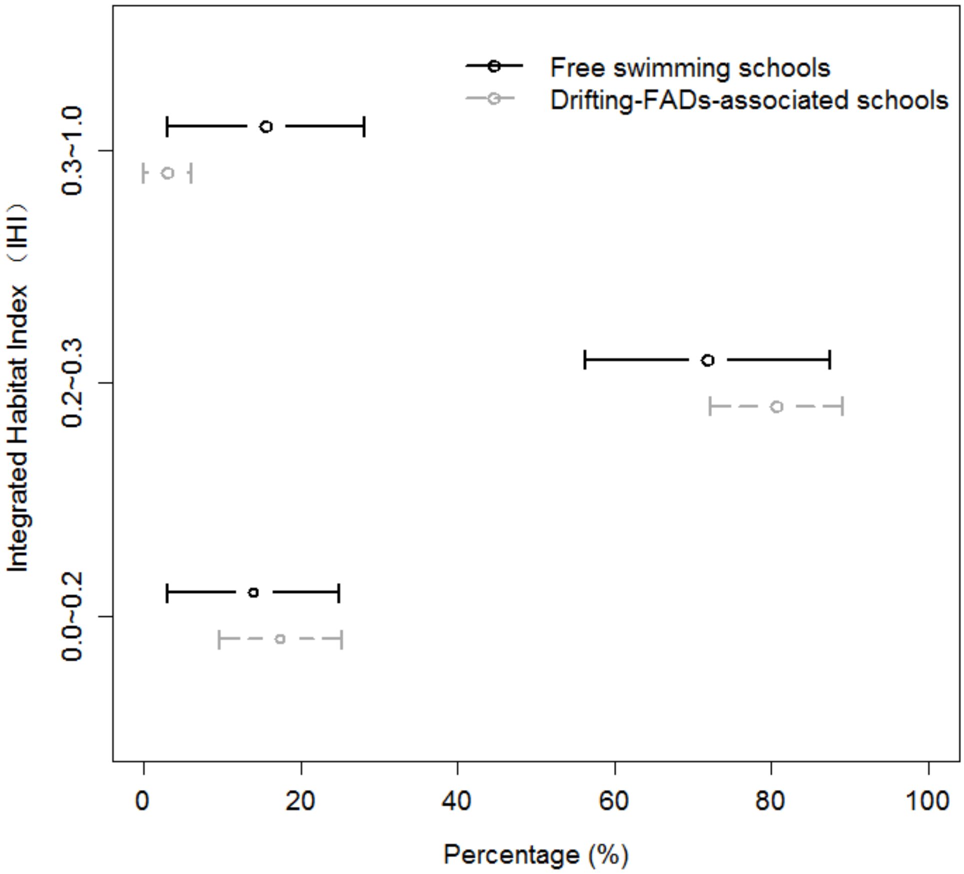

Fig.4. Bootstrapped 95% CIs of Integrated habitat index (*IHI*) portions for skipjack associated to drifting fish aggregation devices (FADs) and caught on free swimming schools.

The 1000 bootstrapped 95% CIs of *IHIs* means estimated ranged from 0.1997 to 0.3146 for free swimming schools and 0.1767 to 0.1972 for associated schools. There was no overlap in the CIs for *IHI* means for the two schools, and overall the habitat quality for free swimming schools was higher than for associated schools (Fig. 5). The 1000 bootstrapped 95% CIs of *IHIs* variances for free swimming schools [0.0044, 0.0645] was much wider than those for associated schools [0.0015, 0.0032]. This suggests that free swimming schools were found in a wider variety of *IHIs* compared to associated schools.

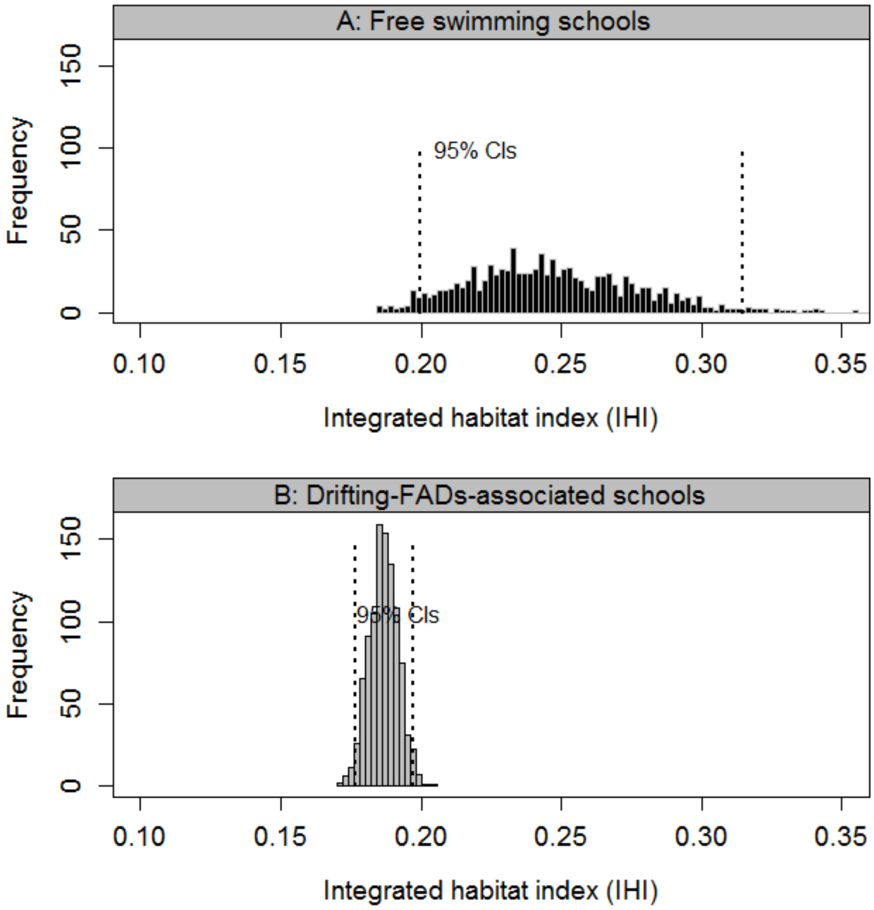

Fig.5. Range of bootstrapped integrated habitat index (*IHI*) for skipjack (A) associated to drifting fish aggregation devices (FADs) and (B) caught on free swimming schools.

Discussion

Habitat quality for free swimming and associated schools

The habitat model in this study examines the effect of temperature and spatial factors on the distribution of skipjack. The habitat modeling shows that free swimming schools were caught in habitat quantified as 0.1997-0.3146, a broader habitat selection range compared to associated schools caught in habitat quantified as 0.1767-0.1972 (Fig. 5). The quality of habitat is influenced by the biotic and abiotic environments and prey availability is thought to be a significant biotic contribution to habitat quality (Sund et al., 1981; Lebourges-Dhaussy et al., 2000).

Tropical tunas inhabit open oceanic waters that have low productivity with "patchy" and relatively scarce prey resources. Oceanic conditions that favor high concentrations of prey may only last a few days to a few weeks (Pitcher, 1995). This could mean tuna behavior has evolved to adapt to such a dynamic and patchy environment. The aggregation behavior of tuna is believed to increase the efficiency of prey searching (Pitcher and Parrish, 1993). Tunas break into small schools when resources are scarce and form larger schools when resources are abundant (Roger, 1994). Tunas also associate with dolphins to track prey by making use of their echo-locating abilities (Clua and Grosvalet, 2001). These behavioral characteristics of tunas describe the responsiveness of tunas to the dynamic distribution of their prey in an oceanic environment. This active search behavior might explain higher habitat quality and wider range of habitat selection of the free swimming schools seen in this study (Fig. 5).

The overall higher habitat quality for free swimming schools can be explained with additional hypotheses. In many cases, free swimming schools are caught during feeding events (SPC, 1989), implying that free swimming schools are caught in locations where prey availability, and subsequently habitat quality, may be naturally higher than those for associated schooling counterparts. Another explanation for wider range of habitat selection could be attributed to a purse seine fishery for free swimming schools which operates in a larger area (Wang et al., 2014), resulting in a wider range of *IHI* values. It should be noted that fishermen do not usually set on free swimming school when they observe the school size is small (less than 20 t) and sometimes the catch is only the part of fish school (the remainder escape from the encirclement), both of which can cause the uncertainty of *IHI* calculation for free schools to increase.

Deployment of drifting FADs is dependent on well-defined current structures as well as socioeconomic factors influencing fishermen, rather than high quality tuna habitat (Hallier and Gaertner, 2008; Scott and Lopez, 2014). Therefore, the movements of FADs are presumed to follow those of oceanic currents (Hallier and Gaertner, 2008). Fish associating with these drifting FADs for significant periods of time are consequently exposed to habitats where FADs pass through. The possibility of an associated school encountering high-quality habitat tends to be reduced compared to free swimming schools to some extent, as suggested by our study. It is hypothesized here that the change in active search behavior is interrupted in tunas associated with FADs, possibly providing an explanation for the lower *IHI* values for associated school. Alternatively, Robert et al. (2014) provided a plausible interpretation that tunas aggregate around floating objects when they are in a poor condition. One scenario could be that tunas in free schools experiencing low foraging success (i.e., a low condition) could preferentially associate with floating objects to find conspecifics, form larger schools, and then be more efficient when foraging. This interpretation also supports the notion that skipjack tuna associated with FADs stay within poor quality habitat.

The higher and the wider variety of *IHI* values for free swimming schools is this study offer support for many of the aforementioned hypotheses including: active search behavior, occurrence in locations with increased prey availability, larger fishing grounds, interruptions of active search behavior due to fish (tuna or prey fish?) association with FADs, the instinct of preferentially associating with floating objects to find conspecifics when they are in a poor condition, or a combination of these factors.

In addition to habitat quality, the distances of both free swimming schools and associated schools to the closet potential habitat can be used as proxy to evaluate potential impacts of FADs on habitat selection for tuna, e.g. Druon et al. (2015) developed an ecological niche modeling (ENM) approach to describe the suitable habitat of skipjack and juvenile yellowfin tuna in the tropical Atlantic and west Indian Oceans. They found that that drifting FAD-associated fishing may drive part of tropical tunas away from productive habitats in the eastern tropical Atlantic while low, if any, influence was found in the western Indian Ocean due to major differences in hydrographic regimes and dynamics of productive habitat.

Future Research

In this study, the hypotheses supported by our results were examined, but other environmental factors, such as oceanic circulation and primary production (chlorophyll-a concentration), may affect food availability and subsequent tuna distribution in addition to water temperature (Lehodey et al., 1998; Lebourges-Dhaussy et al., 2000). However, since this study was based on a fishery-dependent survey with onboard scientific observers, not all potential habitat variables are available. If these additional environmental variables were available, the habitat model may provide a better comparison of habitat quality between the free swimming and associated schools. Fisheries dependent data also has limitations in describing species spatial distribution (Song and Zhou, 2010). Thus, further research should be conducted to reduce uncertainty in quantifying habitat quality with the inclusion of fisheries independent data for increased spatial coverage to further explore the hypotheses born from this study.

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