SCIENTIFIC COMMITTEE
SIXTH REGULAR SESSION

10-19 August 2010
Nuku'alofa, Tonga

Vertical behaviour and the observation of FAD effects on tropical tuna in the warm-pool of the western Pacific Ocean

WCPFC-SC6-2010/FT- IP-01

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Vertical Behavior and the Observation of FAD Effects on Tropical Tuna in the Warm-Pool of the Western Pacific Ocean

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Abstract Archival and acoustic tagging were carried out in the exclusive economic zone (EEZ) of Papua New Guinea (PNG) in the western Pacific Ocean during 2006–07 to investigate the vertical behavior of tropical tuna found in association with large arrays of anchored FADs. Industrialized purse-seine fishing on anchored FADs has existed in the PNG EEZ for more than a decade. Archival tags were implanted in bigeye ($n = 40$; length 40–90 cm FL) and yellowfin (214; length 42–126 cm FL) tuna in the Bismarck and Solomon Seas. Acoustic tags were released in the same areas in 195 tuna (10 bigeye, 116 yellowfin, 69 skipjack). In addition, 27 tuna (eight bigeye, 19 yellowfin) received both an archival and an acoustic tag. Archival tag data from 32 recaptures were categorized into the three distinct vertical behavior modes for bigeye, and the three distinct modes for yellowfin that have been described in the published literature. The depth distribution for each of the categories was then calculated to examine potential vulnerability to industrial purse-seine capture in this region. A region-specific analysis was considered important as oceanographic conditions in this region are distinctly different to the conditions reported in the published literature from other locations. Analysis of acoustic data reveals short residence times at FADs and strong school cohesion. Vertical behavior of skipjack, yellowfin and bigeye tuna that were simultaneously present at the same FAD, as determined by depth transmitting acoustic tags, suggested some vertical separation of these species. However, there was a high degree of depth overlap, particularly during early morning hours when purse seining on floating objects normally occurs in this region. This overlap limits the potential for targeting particular species or size classes of tuna through fishing depth selection. This observation was confirmed from the archival tag depth records for yellowfin and bigeye during the same time period regardless of behavior type exhibited. The recapture of bigeye and yellowfin tuna implanted with both acoustic and archival tags allowed the observation of the natural vertical behavior of these fish when they were close to anchored

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J.L. Nielsen et al. (eds.), *Tagging and Tracking of Marine Animals with Electronic Devices*,
Reviews: Methods and Technologies in Fish Biology and Fisheries 9,
DOI 10.1007/978-1-4020-9640-2_10,

FADs equipped with acoustic receivers. Occupation of shallow (<100 m) depths over a 24 h period was identified as the dominant behavior exhibited on FADs.

Keywords Bigeye · Yellowfin · Skipjack · Archival tag · Acoustic tag · Papua New Guinea

Introduction

Tropical tunas are known to associate with floating objects (Dagorn and Fréon, 1998; Adam et al., 2003) and their vertical behavior has been observed to change during such periods of association (Holland et al., 1990; Cayré, 1991; Schaefer and Fuller, 2005; Dagorn et al., 2007). In particular the vulnerability of juvenile and smaller adult size classes of skipjack, yellowfin and bigeye tuna to purse-seine fishing increases as more time is spent in accessible depth strata when associating with floating objects (Freon and Dagorn, 2000). In the Western and Central Pacific Ocean (WCPO), which accounts for close to half of world tuna production, a rapid expansion has occurred in the use of anchored/fixed and free-floating/drifting Fish Aggregation Devices (FADs). In particular, large-scale deployments of anchored FADs in the Exclusive Economic Zone (EEZ) of Papua New Guinea (PNG) have been conducted since 1996 to assist the development of domestic purse-seine and processing capacity. Increasing dependence on FAD-associated fishing across the WCPO fishery has lead to steadily increasing fishing mortality on small size classes of bigeye and yellowfin tuna with negative impacts on the status of stocks (Secretariat of the Pacific Community unpublished data). In order to mitigate these impacts, we need to better understand the vertical behavior of tuna in mixed-species floating object aggregations. Such understanding may contribute to the development of methods to avoid fishing mortality on small bigeye and yellowfin while continuing to harvest skipjack, which are considered in a robust stock condition (Secretariat of the Pacific Community unpublished data).

Archival and acoustic tags are useful tools for investigating fine scale behaviors and habitat preference. Archival tags can record environmental variables such as fish depth, and external temperature at fine time scales with light intensity measurements used to provide geolocation estimates over time (Gunn and Block, 2001). Acoustic tags emit a coded acoustic pulse train that can be received and recorded by an external receiver (Klimley and Holloway, 1999). Consequently, the receivers can be used to monitor when a tagged fish is within a detectable distance of the receiver (Dagorn et al., 2007). The coding of the signal sent by the acoustic tag can also be configured to vary depending upon the fish depth. Consequently, information can be obtained on not only the presence of the fish but also on its depth at fine time steps analogous to archival data without requiring the recapture of the fish and recovery and data retrieval from an archival tag.

Archival tags have been used in a number of studies outside of the equatorial WCPO to examine tuna behavior, including the interaction with FADs (Schaefer and

Fuller, 2002; Schaefer et al., 2007). Information on the vertical movements of skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares*) tuna in the Eastern Pacific Ocean (EPO) and Indian Ocean have indicated movements to be predominantly restricted to the mixed layer with yellowfin moving below the thermocline for relatively short periods (Dagorn et al., 2006; Schaefer and Fuller, 2007; Schaefer et al., 2007). In comparison, bigeye (*T. obesus*) can occupy deeper habitats and regularly forage within the deep-scattering layer (Dagorn et al., 2000; Schaefer and Fuller, 2002; Brill et al., 2005). Differences in vertical structure of the water column or prey availability and composition are likely to yield different depth patterns in different oceanic regions (Arrizabalaga et al., 2008). For example, the thermocline in the Western Pacific is much deeper than that reported for the EPO (Durand and Delcroix, 2000). Consequently, we could expect vertical behavior and the time spent by individuals in water depths vulnerable to fishing gear to differ between regions in response to the thermoregulatory and life history needs of each species and age/size class. Yellowfin, which is thermoregulatory restricted (Brill et al., 1999), could be expect to use deeper habitats in the WCPO than EPO in response to the greater depth of warmer water. In addition, the majority of fish tagged in previous studies have been larger size classes (>90 cm) and there is minimal information available on the smaller size classes (40–90 cm) that dominate the catch of purse-seine fisheries in PNG (Secretariat of the Pacific Community unpublished data). Therefore, an understanding of the depth distribution of tropical tunas and the impacts of FADs on vertical behavior requires the collection of data from the physical environments and fisheries unique to each study area.

In this paper we present vertical movement and depth information from archival tags returned from a tagging study of 40–130 cm FL tuna that commenced in Papua New Guinea in 2006. We supplement this archival tag information with depth and FAD presence/absence data recorded from acoustic tags deployed during the same study. We use this information to identify potential similarities and differences in vertical habitat behavior between the WCPO and elsewhere for bigeye and yellowfin tuna and demonstrate a method for confirming vertical behaviors associated with FADs.

Materials and Methods

Archival and acoustic tags were deployed in yellowfin and bigeye tuna in the PNG EEZ during two cruises that took place in Aug–Nov 2006 and Feb–May 2007. The study area encompassed the Bismarck Sea, western Solomon Sea and areas immediately north of Manus Island and around the northern coast of Bougainville Island (Fig. 1). Tagging was conducted on the chartered FV Soltai 6, a 27 m, 103 gross-t commercial pole and line fishing vessel from the Solomon Island based company Soltai Fishing and Processing Ltd. Fish were captured during pole and line operations during the day and at night by using hand lines or rod and reel techniques. Smaller bigeye and yellowfin (< 70 cm FL) were prioritized for archival tagging

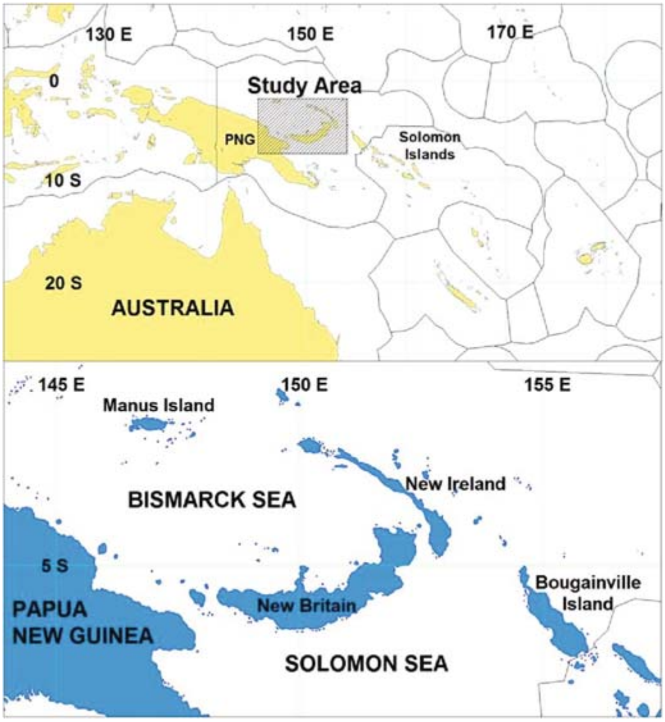

Fig. 1 Map of the study area. *Top panel* shows the study area within the western equatorial Pacific Ocean. *Bottom panel* provides detail and place names relevant to the study

during pole and line fishing as fish condition was not compromised by the fishing technique. Larger sized fish (> 70 cm FL) were caught with rod and reel or hand line during the night and lifted from the water using a purpose-built, dedicated sling, to minimise injury or stress.

Two different size classes of archival tag were used: (1) the larger LTD-2310 (Lotek Wireless, Newmarket, Canada) and the Mk9 (Wildlife Computers, Redmond, USA) which were surgically implanted into fish 60 cm and larger; and (2) the smaller LTD-2410 and LTD-1110 (Lotek Wireless, Newmarket, Canada) which were implanted into fish 40 cm and larger. Depth and ambient temperature were recorded each minute for LTD-2310 and Mk9. The LTD-2410 has limited memory capacity (128 Kb) and to extend the period of sequential records for depth and ambient temperature the tag was programmed to record every five minutes. The LTD-1110 model also has limited memory and only records depth. The sampling interval for this tag is pre-programmed by the manufacturer. The sampling interval also varies with the duration of tag deployment (seven and three minute intervals were observed in this study).

All acoustic gear was manufactured by VEMCO (a division of AMIRIX Systems Inc.). The project deployed individually coded V9 tags and coded V9P tags that provide pressure data convertible to depth with an accuracy of 0.5 m. Acoustic receivers (VR2-500) were mounted directly to anchored FADs to record presence/absence data using 4 m of 10 mm galvanized chain and shackles. The reception range of VR2 receivers mounted in this fashion with V9 and V9P tags is approximately 600 m but can vary depending on ambient noise in the environment. The tags were programmed to transmit at random intervals to reduce the likelihood of data collisions between V9 and V9P tags (60–180 and 40–120 s respectively). Acoustic receivers were mounted and acoustic tagged tuna were released on anchored FADs within five discrete clusters of FADs in the Bismarck Sea and western Solomon Sea. Acoustic releases were made in three areas of high FAD density (cluster A, B, D in Fig. 2) and in two areas of lower FAD density (cluster C, E in Fig. 2). Acoustic receivers were deployed on FADs in clusters A and B during the period 30 September–1 October 2006 and retrieved between 16 and 24 October 2006 to test the attachment and retrieval systems and procedures. FADs in cluster D were equipped with acoustic receivers from 21 to 24 March 2007, and retrieved on 14 April 2007. FAD cluster C was monitored acoustically from 26 March to 6 May 2007 while FAD cluster E was equipped with acoustic monitors from 8 March to 9 May 2007. Acoustic receivers in FAD clusters C, D and E were retrieved, downloaded and replaced at two to five week intervals depending on vessel schedule and sea conditions.

Tuna selected for archival or acoustic tagging were placed in a smooth vinyl tagging cradle or left in the landing sling if greater than 10 kg. The fish was immediately assessed by visual examination for signs of damage or poor condition. If it was judged suitable for electronic tagging, its eyes were immediately covered

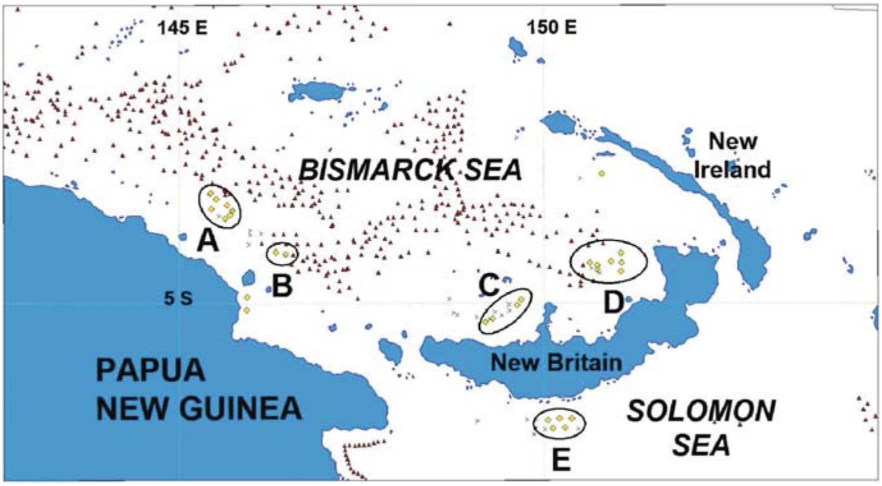

Fig. 2 The location of anchored FADs (*triangles*) and FADs equipped with acoustic receivers (*diamonds*) in the Bismarck and Solomon Seas ("X" symbols indicate former FAD sites not occupied during the study period). Letters A–E refer to groups discussed in the text

with a wetted artificial chamois cloth, length to the nearest cm (FL) was measured, a sea water hose inserted in its mouth to irrigate the gills, the hook removed and an electronic tag(s) was surgically implanted. Implantation methods followed those outlined in Schaefer et al. (2007). Each fish was also marked with a conventional dart tag placed below the second dorsal fin and then released. The tagging operation lasted between 50 sec and two minutes. Suturing was used to close the body cavity incision for bigeye and yellowfin but not for skipjack. Instead for skipjack, the body cavity incision was closed using three stainless steel staples delivered by a 3 M 35 W surgical staple gun. All other tagging procedures were identical for the implantation of the archival and acoustic tags for the three species.

Total archival tag releases were 281 comprising 48 bigeye and 233 yellowfin tuna (Table 1). The releases on schools associated with anchored FADs (201) were widely scattered throughout the Bismarck Sea, the Solomon Sea and on the east side of Bougainville Island. Drifting FADs, seamounts and free schools were fished opportunistically and 80 fish were tagged from these location. The size distribution of tagged bigeye ranged from 40 to 90 cm FL and tagged yellowfin ranged from 42 to 126 cm FL.

A total of 222 acoustic tags were deployed in bigeye (18), yellowfin (135) and skipjack (69) tuna (Table 1). Of these releases, 195 tuna received only an acoustic tag of which 58% were depth recording V9P tags. The size range of the fish implanted with acoustic tags was bigeye (range 47–74 cm FL), yellowfin (range 37–76 cm FL) and skipjack (range 33–53 cm FL). Twenty seven bigeye and yellowfin were implanted with both an archival and an acoustic tag. This double electronic tagging provided the opportunity to verify vertical behaviour when an individual was known to be associated with receiver-equipped FADs.

Most of the archival tags spent some time at minus 20°C in the brine wells of fishing or transshipment vessels post-recapture. Six tags were returned to their manufacturer for data acquisition as they stopped operating due to this cooling process. Archival and acoustic data were downloaded from the tags or receivers using software provided by the tag manufacturers.

Table 1 Release and tag details for the three tuna species. The school type "Other" includes drifting FAD, floating log, whale shark, free schools, current/tide line and seamount

		School type at release		
Species	Type	Anchored FAD	Other	Total
Bigeye	Archival	33	7	40
	Acoustic	10		10
	Both	8		8
Yellowfin	Archival	141	73	214
	Acoustic	116		116
	Both	17	2	19
Skipjack	Acoustic	69		69

Data Analysis

The depth records from archival tags were initially analyzed from day 30 after release to avoid possible behavioral changes imposed from the process of tagging (Schaefer and Fuller, 2002; Schaefer et al., 2007). Since some archival tags deployed did not have a light sensor it was impossible to determine night and day periods for all tags. In the absence of this information the depth and temperatures habitats for each individual were binned into 10 m depth intervals and examined in the 0800–1600 (diurnal), 1600–2000 (dusk), 2000–0400 (nocturnal) and 0400–0800 h (dawn) time periods. These corresponded to time periods for which bigeye (Dagorn et al., 2000; Holland et al., 1990; Schaefer and Fuller, 2002) and yellowfin (Dagorn et al., 2006; Schaefer et al., 2007) have been observed to shift their vertical behavior patterns. For each individual, the track of vertical habitat from day 30 to point of capture was categorized into the behaviors identified in the published literature (Schaefer and Fuller, 2002, 2007; Schaefer et al., 2007). We did this to evaluate whether the vertical behavior patterns described for tropical tuna were suitable for smaller sized fish tagged in this study. We also recorded instances when the observed vertical behavior over a 24 h period could not be classified into these existing descriptions. Nomenclature that describes each behavior is consistent with that used in the literature (Schaefer and Fuller, 2002, 2007; Schaefer et al., 2007). As the sample sizes were small we chose this qualitative method over more quantitative approaches. The method also replicates that used in recently published studies from the EPO, thereby providing opportunities for direct comparison with these results.

Bigeye were categorized into one of three behaviour types for each 24 h time step: (type 1) A visually obvious diel pattern where fish occupy shallow habitats at night, vertically descend at dawn and occupy deep habitats during the day before ascending to shallower habitats at dusk; (type 2) fish use shallow habitats at night, descend to deeper habitats at dawn but demonstrate regular movement between shallower and deeper habitats throughout the diurnal periods (i.e. bounce diving; see Schaefer et al., 2007 for definition); and (type 3) fish occupy shallow habitats throughout the 24 h period (Schaefer and Fuller, 2002). Yellowfin were also categorized into one of three behaviour types for each 24 h time step (Schaefer et al., 2007): types 1 and 2 were identified by a visually obvious diel pattern where fish occupy shallow habitats at night, vertically descend at dawn and occupy deep habitats during the day before ascending to shallower habitats at dusk. Differentiation between (1) and (2) was determined by the diurnal depths of the fish, with type 1 diurnal depth typically not exceeding 150 m and type 2 depths typically greater than 150 m. Bounce diving between shallow and deeper habitats could be frequent in both type 1 and 2 during diurnal periods. Type 3 behavior was classified as occupation of shallow habitats throughout the 24 h period. We also collected maximum depth and duration of any deep dives observed in the tracks for both species. Deep-dives were classified as single dives in excess of 500 m (Schaefer and Fuller, 2002; Schaefer et al., 2007). We report information on surfacing behavior (Schaefer and Fuller, 2007;

Schaefer et al., 2007) for nine yellowfin where depths were recorded every one minute. Surfacing behavior is defined as consecutive records in excess of 10 min where the fish was in depths of 10 m or less (Schaefer et al., 2007). All other archival tags recovered were programmed to record at intervals grater than one minute and individuals could easily have descended to depths greater than 10 m and then return to the surface in the time-period between records without our knowledge.

Acoustic records from double tagged fish were only recorded in the period from time of release to day 30 of the track, the period when behavioral changes due to the process of tagging could be expected (Schaefer and Fuller, 2002, Schaefer et al., 2007). To examine the plausibility of this "tagging-effect" hypothesis we initially tested whether the distributions of vertical depth in each behavior type in this period differed to the depth distributions in the post 30 day period using two-tailed Kolmogorov – Smirnov test (KS). If no difference in distribution was detected, we considered it appropriate that the behaviors observed from the acoustic records were unlikely to be strongly influenced by the tag implantation procedure. As the acoustic records were measured from receivers placed on FADs we also consider that the behavior observed to be a reliable observation of FAD associated behavior if no difference in distribution was detected.

The depth records from the acoustic tagged fish were similarly binned into 10 m depth intervals and the depth distribution between the same time periods and between species compared using KS. The mean thermocline (depth of the 18° and 12° Celsius isobaths) in the Bismarck Sea was estimated by pooling all depths records from the LTD-2310 and Mk9 archival tags at 18°C and at 12°C and then calculating the average depth and 95% confidence interval for each temperature.

Results

Archival Tag Recoveries

To 31 December 2007, 33 archival tags (10 bigeye and 23 yellowfin) had been recovered including six fish that were also tagged with acoustic transmitters. All tag recoveries occurred within the Bismarck Sea. The tags were recovered on board catcher vessels with the exception of two that were found in a Thailand cannery. Depth sensor failure/malfunction occurred in one tag, reducing the number of tags included in the analyses to 32. Complete data records were available from 31 tags with a partial record available from one tag. We detected no difference in the pooled depths distribution in the release to 30 day period and the post 30 day period for type 1 2 or 3 bigeye and yellowfin behaviors (Table 2) indicating that the implantation procedure did not have a large effect on the behaviors observed. The depth of the 18° and 12° Celsius isobaths estimated from the archival tags was 200 ± 1 m and 300 ± 1 m, respectively.

Table 2 KS statistics for tests examining the difference between pooled depths distribution in the release to 30 day period and the post 30 day period for each of the observed bigeye and yellowfin behaviors

	n (0–30 days)	n (30 + days)	*D*	P
Bigeye				
Type 1	40655	2304	0.052	>0.05
Type 2	58468	11732	0.080	>0.05
Type 3	9793	17383	0.054	>0.05
Yellowfin				
Type 1	254856	499854	0.032	>0.05
Type 2	148773	54107	0.047	>0.05
Type 3	63335	4389	0.042	>0.05

Vertical Depth Behavior

All three vertical behaviors described for bigeye in the literature were observed in all individuals where the deployment duration was longer than 30 days (Fig. 3). During nocturnal time periods (2000–0400) all bigeye occupied shallow depths typically <100 m from the surface (Table 3, Fig. 3). Deep diving was observed in each bigeye behavior type, typically occurring but not restricted to the dawn (0400–0800) and dusk (1600–2000) time periods. The depth range of deep dives was 500–1498 m and dive duration estimated from 10 to 60 min. During typical purse seine setting times on floating objects (0400–0800), >50% of records were within 200 m of the surface (Table 4, Fig. 3). When exhibiting type 3 vertical behaviour, >60% of records were within 100 m and >90 % records within 200 m of the surface (Table 4, Fig. 3). One double tagged bigeye (67 cm FL) was recovered where both archival and acoustic tag records were simultaneously obtained. The blue trace in Fig. 4a indicates 20 days of vertical behaviour (20 October–9 November 2006) from the archival tag data. Type 3 bigeye vertical behaviour was recorded for approximately 13 days from 20 October–2 November. Acoustic transmissions were received by the FAD mounted acoustic receiver for 3.5 days post-tagging, confirming that type 3 behavior was exhibited whilst associated with this FAD. The receiver was recovered at 3.5 days and not replaced.

All three vertical behaviors described for yellowfin in the literature were observed in all individuals where the deployment duration was longer than 30 days (Fig. 5). During nocturnal time periods all yellowfin occupied shallow habitats typically <100 m from the surface (Table 3, Fig. 5). Bounce diving was observed regularly in behavior types 1 and 2. An additional behavior was also observed in one yellowfin that was extremely similar to type 1 bigeye. This fish occupied deep (200 m plus) water in diurnal periods with no records of bounce diving, before occupying shallower habitats at night. This behaviour was observed on several occasions in its track. Deep diving was observed in each yellowfin behaviour type. The depth range of deep dives was 500–1315 m and dive duration estimated to vary from

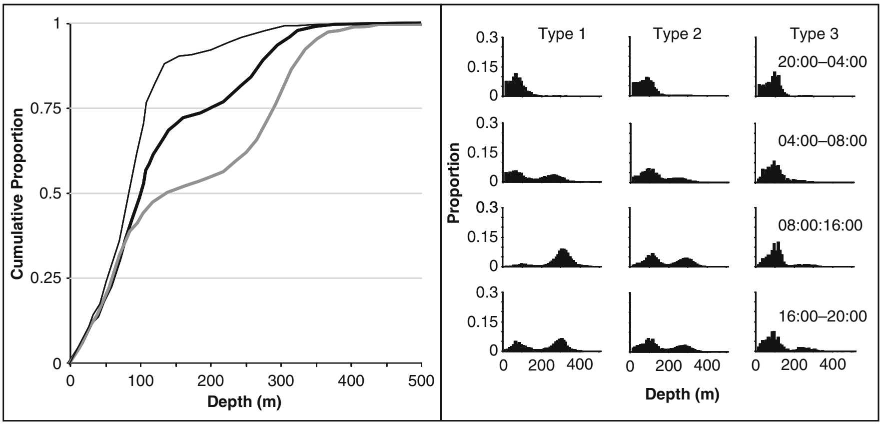

Fig. 3 Cumulative proportion by depth (*left panel*) for type 1 (*grey*), type 2 (*thick black*) and type 3 (*thin black*) bigeye behaviors and frequency of observation histograms (proportion) for each 10 m depth interval (*right panel*) for each behaviour types in nocturnal (2000–0400 h), dawn (0400–0800 h), diurnal (0800–1600 h) and dusk (1600–2000 h) time periods

10 to 20 min. Surface-oriented events were also observed in yellowfin. The number of surface events per day ranged from three to 17 and duration ranged from 10 to 166 min (average 21 min, $\text{quartile}_{25} = 12$ min, median = 16 min, $\text{quartile}_{75} =$ 23 min). The surfacing events were observed in all three behavior types, with the majority (70%) occurring at night, 24% observed in dawn and dusk periods and only 8% observed during the day.

The vertical depths used during the typical purse seine setting times on floating objects by yellowfin were similar to those observed for bigeye with >50% of records within 200 m of the surface (Table 4, Fig. 5) during these hours. When exhibiting type 3 vertical behaviour, >80% of records were within 100 m and >90% records within 200 m of the surface (Table 4, Fig. 5). One double tagged yellowfin (72 cm FL) was recovered where simultaneous vertical behaviour from an archival and a coded depth sensing acoustic tag was obtained. Figure 4b shows a seven day record (27 March–3 April 2007) of archival tag data (top panel in blue) for this fish and the 3.5 days within this time period the yellowfin tuna was also recorded as being in close proximity to a receiver-equipped anchored FAD (bottom panel in red). The depth record from both the archival tag and acoustic tag are classified as type 3 and confirm that this behavior was exhibited whilst associated with this FAD. The vertical behaviours reported by both tag types are consistent with each other but not exactly synchronous due to different sampling rates and slightly different time scales.

Multi-Species School Depth Records

On a single FAD within cluster E (Fig. 2), the acoustic depth records from a multi-species school (two bigeye, four skipjack and six yellowfin) were recorded. The ver-

Table 3 Summary statistics for bigeye and yellowfin for each vertical behavior for nocturnal (2000–0400 h), dawn (0400–0800 h), diurnal (0800–1600 h) and dusk (1600–2000 h) time periods

Species	Vertical behavior types	Period (h)	Mean (m)	s.d.	Min (m)	Max (m)	Quartile (m)		
							25%	50%	75%
Bigeye	1	2000–0400	70	68	0	1400	34	60	86
		0400–0800	150	114	0	773	53	120	242
		0800–1600	277	85	0	1294	257	295	323
		1600–2000	202	119	3	1450	84	239	293
	2	2000–0400	75	61	0	1465	37	71	97
		0400–0800	125	84	0	658	65	102	181
		0800–1600	179	102	0	1498	96	148	271
		1600–2000	152	106	0	1459	75	116	242
	3	2000–0400	77	60	0	1417	44	78	101
		0400–0800	91	54	0	314	55	84	113
		0800–1600	105	81	0	1482	65	93	116
		1600–2000	107	84	0	598	54	84	122
Yellowfin	1	2000–0400	41	42	0	1091	7	38	72
		0400–0800	81	61	0	789	28	77	120
		0800–1600	125	67	0	1315	81	122	166
		1600–2000	82	62	0	561	31	73	121
	2	2000–0400	46	44	0	291	5	38	74
		0400–0800	97	73	0	561	34	88	151
		0800–1600	178	82	0	1238	117	186	234
		1600–2000	105	80	0	559	43	89	159
	3	2000–0400	41	38	0	314	6	31	67
		0400–0800	62	52	0	306	18	55	93
		0800–1600	70	57	0	591	27	64	100
		1600–2000	56	54	0	512	13	46	79

tical behavior recorded for each species was consistent with the shallow day/night behavior (type 3) described for yellowfin and bigeye (Fig. 6). Vertical separation of depth was observed between bigeye – skipjack and bigeye – yellowfin (bigeye versus skipjack, KS, $n = 524\text{–}1143$, $D = 0.416$, $P<0.05$; bigeye versus yellowfin, KS, $n = 524\text{–}2987$, $D = 0.350$, $P<0.05$); however, no statistically significant difference was detected between skipjack and yellowfin (KS, $n = 1143\text{–}2987$, $D = 0.082$, $P>0.05$). Bigeye habitat was deeper than skipjack or yellowfin (Fig. 6).

FAD Residence Time

At FAD cluster D, 20 skipjack and 27 yellowfin were monitored on six receiver-equipped FADs. Acoustic transmissions from all 47 tuna halted within 21 h of deployment indicating very short-lived residence times (post-tagging) with 73% of the fish leaving their FAD of release within six hours. Mean residence time

Table 4 Cumulative proportion of bigeye and yellowfin records at depth (m) for each vertical behavior for nocturnal (2000–0400 h), dawn (0400–0800 h), diurnal (0800–1600 h) and dusk (1600–2000 h) time periods

			Cumulative proportion of records at depth (m)		
Species	Vertical behavior types	Period (h)	<100	<200	<300
Bigeye	1	2000–0400	0.83	0.97	0.98
		0400–0800	0.46	0.62	0.92
		0800–1600	0.07	0.14	0.55
		1600–2000	0.30	0.43	0.80
	2	2000–0400	0.77	0.97	0.99
		0400–0800	0.48	0.79	0.97
		0800–1600	0.28	0.56	0.87
		1600–2000	0.40	0.66	0.93
	3	2000–0400	0.75	0.98	0.99
		0400–0800	0.65	0.94	0.99
		0800–1600	0.57	0.90	0.98
		1600–2000	0.63	0.83	0.97
Yellowfin	1	2000–0400	0.89	0.99	0.99
		0400–0800	0.64	0.96	0.99
		0800–1600	0.36	0.89	0.99
		1600–2000	0.66	0.96	0.99
	2	2000–0400	0.88	0.99	1
		0400–0800	0.56	0.90	0.99
		0800–1600	0.2	0.57	0.95
		1600–2000	0.55	0.86	0.99
	3	2000–0400	0.91	0.99	0.99
		0400–0800	0.8	0.98	0.99
		0800–1600	0.75	0.97	0.99
		1600–2000	0.85	0.97	0.99

post-release was only six hours and no acoustic tagged tuna were recorded on any receiver-equipped FAD other than their FAD of release. No purse seine activity or other significant source of fishing mortality took place in this area during the time of the experiment. Departure times were closely timed and nearly simultaneous for tuna ranging from 40 to 51 cm FL. At FAD cluster C, 18 skipjack and 23 yellowfin were acoustically monitored at four FADs for a mean residence time of 27.8 h. Seventeen skipjack departed the FAD where they were tagged within 15 h of release. Yellowfin remained at their FAD of release up to nine days post-tagging. A small number of movements between monitored FADs were recorded for yellowfin tuna including two of the larger individuals (64 and 74 cm FL) that remained at an adjacent FAD for 6.5 days before leaving FAD cluster C. At cluster E, 10 skipjack, 38 yellowfin and two bigeye were released on five isolated FADs in the Solomon Sea. Post-tagging residence times were approximately four days. Yellowfin tended to remain associated for longer periods with nine yellowfin recorded at their FAD of release for seven to 15 days.

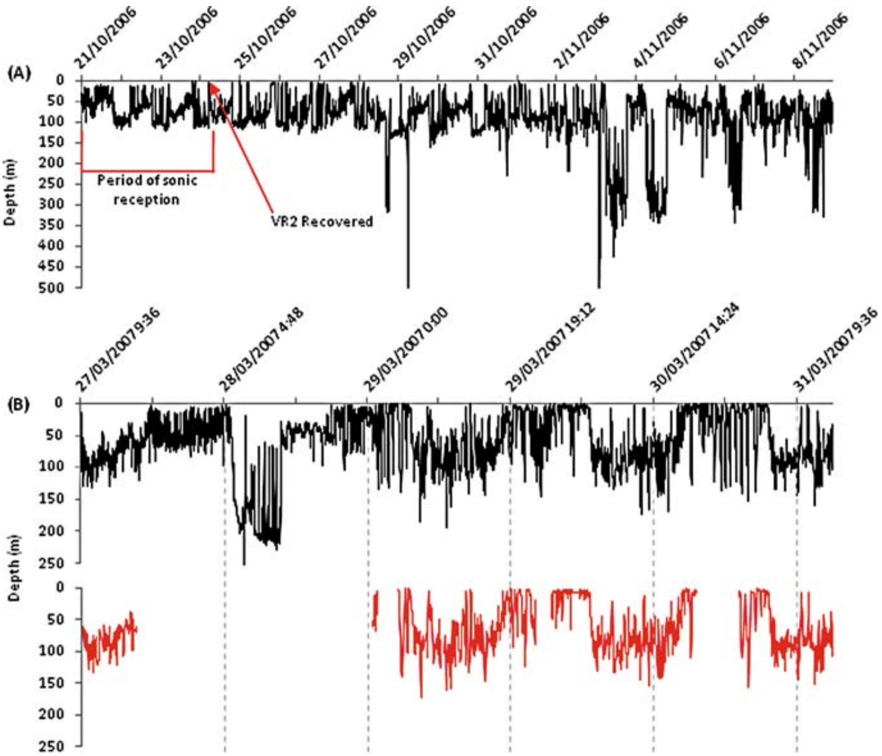

Fig. 4 Archival and acoustic information from tuna double tagged with both tag types. (**A**) A twenty day archival depth record (in meters indicated by blue line) of a 67 cm bigeye tuna. The red bracket indicates the time period when its acoustic tag was received at a FAD-mounted acoustic receiver. (**B**) A seven day archival depth record in meters (*top panel in blue*) of a 72 cm yellowfin tuna double tagged with a depth recording acoustic tag. The *bottom panel* indicates (in *red*) the depth record (m) spanning four days produced by the acoustic tag when it was within range of a FAD-mounted acoustic receiver

Discussion

The observations from this study provide important insights into the habitat use of small size classes of tropical tuna. Strong similarities between the vertical behavior of tropical tuna in the equatorial WCPO and that reported in the equatorial regions of the EPO and elsewhere were observed. Empirical data from the EPO supports hypotheses that the vertical movements of bigeye are strongly influenced by FADs with fish occupying shallower habitats when associated with a FAD (Musyl et al., 2003; Schaefer and Fuller, 2002). Our results concur with these observations. We observed three vertical behavior types in bigeye including the occupation of shallow habitats, typically less than 100 m over a 24 h period. This behavior was observed in the concurrent archival and acoustic records from the recapture of one bigeye with both tag types, confirming that this shallow type 3 behavior is consistent with FAD

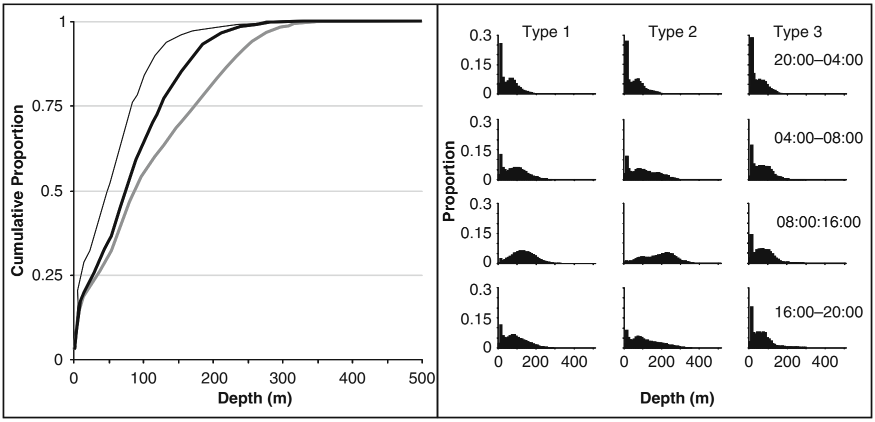

Fig. 5 Cumulative proportion by depth (*left panel*) for type 1 (*thick black*), type 2 (*grey*) and type 3 (*thin black*) yellowfin behaviors and frequency of observation histograms (proportion) for each 10 m depth interval (*right panel*) for each behaviour types in nocturnal (2000–0400 h), dawn (0400–0800 h), diurnal (0800–1600 h) and dusk (1600–2000 h) time periods

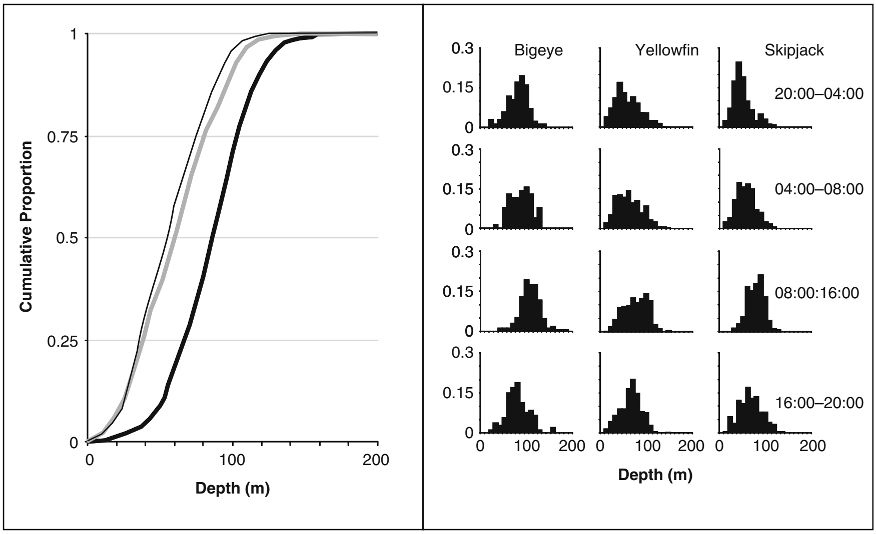

Fig. 6 Multi-species 24 h depth records measured from a VEMCO acoustic receiver on a single FAD; *left panel* is the cumulative proportion for bigeye (*thick black line*), yellowfin (*grey line*) and skipjack (*thin black line*); and *right panel* is depth histograms or each species in nocturnal (2000–0400 h), dawn (0400–0800 h), diurnal (0800–1600 h) and dusk (1600–2000 h) time periods

association. We also observed similar behavior in the archival and acoustic records of a recovered yellowfin that was double tagged. This yellowfin recovery reinforced this link between association mode and vertical behaviour. Acoustic receptions by the FAD-mounted receiver were temporarily lost when the archival record indicated it entered a diurnal deep-diving mode, suggesting it had moved away from the FAD during this period. Type 3 shallow behaviour resumed when it returned within range of the FAD receiver. Whilst the conclusions from two fish must be viewed with caution, the results indicate that the double tagging approach can provide an effective method for collecting data on FAD associated behavior.

The type 1 and type 2 diel behaviors for bigeye observed in this study were also consistent with those observed elsewhere in the Pacific. In the equatorial EPO, type 1 diel behavior was described as occupation of shallow habitats, typically at depths of less than 50 m during nocturnal hours and depths between 200 and 300 m during diurnal hours where water temperatures were 13° and 14°C (Schaefer and Fuller, 2002). Bigeye shifted their average depths in conjunction with dawn and dusk events, with this shift hypothesized as a foraging strategy to track prey-species that comprise the deep-scattering layer (Musyl et al., 2003; Schaefer and Fuller, 2002). Typical diurnal depths observed in this study were 300 m, which also coincided with the 12°C isotherm of the thermocline. The size range of individuals in the EPO study varied between 88 and 126 cm, whereas the bigeye in this study varied between 62 and 67 cm. It is plausible that larger bigeye in the Bismarck Sea are occupying deeper depths during diurnal hours than in the EPO because of the deeper thermocline and preferred temperature isotherms. A study of larger bigeye (74–103 cm) in the nearby Coral Sea observed regular migrations to depths of 450–500 m during diurnal periods at temperatures of 7°C and 9°C (Evans et al., 2008). A similar observation was reported for a 131 cm bigeye in waters near Hawaii and temperatures of 7°C and 10°C, with smaller size classes occupying shallower daytime depth (Musyl et al., 2003).

The dominant vertical behavior of yellowfin was similar to type 2 bigeye behavior with bounce diving during diurnal periods a predominant feature. The characteristics of the bounce dives were also very similar to those reported in the EPO (Schaefer et al., 2007). The majority of bounce dives were restricted to around 150 m (type 1 behavior), but we also observed a second behavior type with bounce dives to an average depth of 200–250 m. Schaefer et al. (2007) hypothesized that bounce diving in excess of 150 m was most probably associated with foraging within the deep scattering layer in the EPO.

Our observation of deep diving behavior for bigeye and yellowfin was also consistent with other studies (Dagorn et al., 2006; Schaefer and Fuller, 2002; Schaefer et al., 2007). The duration of deep dives for bigeye extended for periods up to 60 min supporting the hypothesis that bigeye are physiologically able to withstand lower temperatures and dissolved oxygen levels for extended periods of time (Holland et al., 1992; Lowe et al., 2000). The duration of dives for yellowfin was 10–20 min supporting the hypothesis that they are not physiologically able to withstand conditions in deeper waters for extended time periods (Brill et al., 1999). However, yellowfin were observed to make some dives in excess of 1000 m, which was consistent with the observations of Dagorn et al. (2006) and Schaefer et al. (2007). Surfacing behavior was observed in yellowfin with individuals observed to spend over two hours in the upper 10 m of the water column during diurnal periods. This behaviour is not likely to be related to reproduction as most of the archival data came from juvenile-sized yellowfin. Feeding or FAD influences on behavior are possible explanations for the daytime surfacing behaviour observed in this study.

Our observations on FAD residence times suggest that in the Bismarck Sea, tuna school associations with individual FADs may be short-term and transient in nature, particularly when local FAD densities are high. Several tag release cohorts of smaller sized skipjack, yellowfin and bigeye tuna ($\sim$40–50 cm) were observed to leave the FAD where they were tagged in closely timed groups within 24 h of release. This observation is in contrast to recent studies of FAD residence times in the waters of southern Japan and the Hawaiian Islands. Dagorn et al. (2007) observed mean residence times of Hawaiian yellowfin and bigeye tuna at anchored FADs to be about five to eight days but recorded several continuous residence times of yellowfin up to 65 days. Ohta and Kakuma (2001) recorded similar FAD residence times for yellowfin and bigeye tuna in Japan with longer continuous residence times of up to 55 days observed. One possible factor contributing to the short-term and transient nature of individual FAD associations in the Bismarck Sea may be related to the large number, density and geographic coverage of FADs in PNG which are far higher and extensive compared to FADs in Japan and Hawaii. Faced with so many floating objects that are uniformly spaced at nine to 10 nautical miles apart, the tuna may be moving from one FAD-association to another rather than establishing a longer association with one. The relatively isolated FAD clusters C (four FADs) and E (five FADs) were comparable in number, density and spacing to those observed in Japan and Hawaii. The residence times of tuna at FAD clusters C and E were also similar to those observed in Japan and Hawaii suggesting that fish may remain longer at isolated FADs. However, the study did not acoustically monitor enough FADs for long enough to draw strong conclusions on FAD residence times or any conclusions as to the cumulative retention effect of the large concentration of FADs in the Bismarck Sea. While individual FAD residence times were observed to be short, the cumulative impact of hundreds of FADs may entrain fish for extended periods. Longer-term acoustic studies or results from archival and conventional tag recaptures are needed to address these questions.

The occurrence of simultaneous multi-species departures in our acoustic data observations indicates the possibility of persistent multi-species schooling behavior of similar sized tuna. Synchrony in departure from FADs was the dominant behavior observed in the waters of the Hawaiian Islands (Dagorn et al., 2007; Klimley and Holloway, 1999). In these studies not all the tagged fish at a FAD left on the same day and typically small groups of fish left together while others remained, suggesting that the aggregation of tunas associated with a FAD is comprised of multiple "sub-schools" (Dagorn et al., 2007). We also observed variation in the departure of groups of individuals which supports the "multiple sub-school" hypothesis.

We did not detect a difference in the vertical behaviour patterns between the first 30 days of records and those from post 30 days. The first 30 days is the period when the effects of implantation are hypothesized to impact upon behavior (Schaefer and Fuller, 2002; Schaefer et al., 2007). It is also the period when acoustic records from fish that are tagged and released at a particular FAD are likely to be recorded given the short residency times observed in our study. Our results indicate that it is not unreasonable to utilize the information collected immediately after implantation when characterizing vertical behavior, a result similar to that observed by Musyl et al. (2003).

The depth data collected from archival and acoustic tags for bigeye, yellowfin and skipjack tuna in this study has implications for fishery management. Recent stock assessments for bigeye and yellowfin indicate an increased probability that overfishing reference points are being approached or exceeded (Secretariat of the Pacific Community unpublished data). While the fish in this study did stratify habitats from shallower (yellowfin and skipjack) to deeper (bigeye), the differences were not great enough to suggest that restricting the depth of purse seine nets would be an effective means of completely avoiding small bigeye or yellowfin tuna fishing mortalities. If it is assumed that bigeye type 3 behavior is a reasonable estimate of vertical depths used when associating with FADs, then there may be some opportunity for reducing bigeye fishing mortalities through restricting purse-seine net depths. This is particularly clear when examining the vertical depth distributions between 0400–0800 h, when the majority of floating object sets are conducted in the region. Over 90% of bigeye records were in depths of 200 m or less whereas 65% of records were in depths of 100 m or less. However, our observations suggest that such restrictions would be unlikely to significantly reduce fishing mortalities on small yellowfin tuna and that other management approaches are required to reduce fishing mortalities from purse-seine fishing for this species. The application of double tagging with acoustic and archival tags in this study proved to be useful for identifying behaviors that occurred on FAD's and it may prove a useful method for future experiments and assist in the interpretation of archival data sets. Utilizing such data could allow a model to be constructed that predicts the likelihood of FAD association throughout the individual deployment histories. Such a model might be used to predict the frequency of FAD association as it relates to catchability and the proportion of the population using FADs at a particular time step. These statistics would be of further benefit to stock assessment models.

Acknowledgements This project was funded by Global Environment Fund (Pacific Fisheries Oceanic Management Project), Australian Centre for International Agricultural Research (Assessment of the impact of the PNG purse seine fishery on tuna stocks, with special focus on the impact of fish aggregation devices), French Pacific Fund, NZAID, National Fisheries Authority (Papua New Guinea) and 8th European Union Development Fund (Pacific ACP and OCT Pacific Regional Oceanic and Coastal Fisheries Development Programme). SPC unpublished data can be sourced from the WCPFC web site (www.wcpfc.int/meetings) and then follow links under the heading Scientific Committee to: 3rd Regular Session, then GN-WP-1 (catch statistics) and SA-WP-2 (yellowfin stock assessment); 2nd Regular Session, then SA-WP-2 (bigeye stock assessment); and 1st Regular Session, then SA-WP-4 (skipjack stock assessment). We thank the crew and officers of the Soltai 6, managers within the Soltai Fishing and Processing Ltd, and Augustine Mohiba, Ludwig Kumoru and Luanah Koren (PNG National Fisheries Authority) for their assistance. Tony Lewis, Brian Kumasi, Peter Williams, Don Bromhead, Valerie Allain, Brett Molony, Kim Louen, Sifa Fukofuka, Colin Milar, Adam Langley, Helene Ixeko, Kay Parry, Charles Cuewapuru, Ambrose Orianihaa, William Sokimi and Emmanuel Schneiter assisted with tagging. Brett Molony and Simon Hoyle provided a critical review of this manuscript prior to submission and we thank them for their assistance. We also acknowledge two anonymous reviewers and Alistair Hobday (Associate Editor) for their extremely valuable and insightful comments.

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