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ELECTRONIC TAGGING FOR THE MITIGATION OF BIGEYE AND YELLOWFIN TUNA JUVENILES BY PURSE SEINE FISHERIES

WCPFC-SC15-2019/EB-WP-08

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1. Executive Summary

Uncertainty within the stock assessment for Western Central Pacific Ocean (WCPO) bigeye tuna has caused concern, particularly regarding the level of fishing mortality on small bigeye tuna associated with Fish Aggregating Devices (FADs), and the lack of understanding regarding the drivers of FAD association behaviour. A project was commissioned during 2018-2019 to significantly expand the amount of electronic tags released on drifting FADs in the WCPO, in order to identify the potential for interventions to reduce FAD-related mortality of smaller bigeye and yellowfin tuna. This included new behavioural data obtained via the release of fish tagged with acoustic transmitting 'sonic' tags, capable of transmitting presence and depth information to an acoustic receiver attached to the FAD of release. This paper presents the first review of the data obtained by the project during the Pacific Tuna Tagging Programme CP13 tagging cruise (SC15-RP-PTTP-02, 2019). We summarise the data in the context of FAD residence times, movements and depth distributions, and take an integrated analytical approach by combining oceanographic, fisheries, and biological information to explore potential drivers of these behaviours for bigeye tuna.

During CP13, 179 sonic tagged fish were released, at eight acoustic receiver equipped drifting FADs, providing individual behavioural data for 1846 days from 86.6% of the fish tagged. Data were received from 97 bigeye, 45 yellowfin and 13 skipjack tuna, and metrics of presence and depth distribution during day-time, night-time and a typical purse seine set pre-dawn period were calculated. Using the known location of the drifting FADs during detected association periods, oceanographic and other covariates were linked to individual fish behaviours and examined as explanatory variables in several, preliminary, statistical models.

Observed residence times were consistent with previous electronic tagging studies in the region. Median continuous residence times (CRT) were longest for bigeye tuna (10 days), with much shorter median CRTs for yellowfin (2 days) and skipjack (1 day). The maximum CRT was 50 days, exhibited by a 49cm fork length (FL) yellowfin tuna. The maximum CRT for a bigeye tuna was 30 days, for a 55cm FL fish. For skipjack tuna, the longest CRT was 18 days, for a 55cm FL fish. Depth distributions overlapped between all species while associated with FADs, but were generally shallow and had the greatest overlap during the pre-dawn period. Cohesion of behaviours between fish released into the same school was clear during the initial association event, though after departing the FAD of release, few tagged fish re-associated simultaneously.

Satisfactory generalised additive models were fitted to data of bigeye tuna departures from FADs, and whether they were present at the FAD during the pre-dawn period. For departures, low skipjack tuna biomass, estimated from FAD-attached echo-sounder buoys, was associated with increased departure probability in bigeye tuna. Lower SST and greater changes in sea surface height were associated with a lower probability of departure from a FAD. Quarter and full moon periods, lower sea surface temperatures, and higher local FAD density were all associated with a greater probability of presence of tagged bigeye tuna at the FAD during pre-dawn.

We invite WCPFC-SC15 to:

- Note the preliminary results of this project in the context of identifying potential measures for mitigating against bycatch of undersized bigeye tuna, including the further evidence of high inter-species mixing during typical pre-dawn purse seine set timing and the potential effect of local;
- Note the value of sonic tagging experiments undertaken in 'arrays' of drifting FADs, and their potential to quantify school mixing, local drivers of behaviour, and provide fishery-independent movement data;
- Note the importance of integration across regional projects and programmes to construct a complete picture of the environmental context of observed behaviours; and
- Note the critical importance of continued collaboration with industry and sub-regional partners to undertake effective electronic tagging and integrated analyses.

2. Background

The most recent stock assessment for Western Central Pacific Ocean (WCPO) bigeye tuna indicated that the stock was neither overfished, nor subject to overfishing (McKechnie et al. 2017). However, given the uncertainty within the assessment and the results of previous assessments indicating the contrary, the Western and Central Pacific Fisheries Commission (WCPFC) Scientific Committee called for a precautionary approach until an appropriate target reference point can be agreed upon, which remains the case. One area of particular concern is the level of fishing mortality on small bigeye tuna associated with Fish Aggregating Devices (FADs), and the lack of understanding regarding the mechanisms behind this.

The evidence for altered behaviour in bigeye and yellowfin tuna behaviour in the presence of FADs is unambiguous (Leroy et al. 2013), but the dynamics of residence times, association strength and timing are less clear. Analyses of archival tagging data from these species have suggested the potential for multiple behavioural modes of floating object association (Scutt Phillips et al. 2017, Robert et al. 2012), and some changes in free school behaviours in response to environmental conditions (Abascal et al. 2018). While most of the electronic tagging effort on FAD-associated tuna has been conducted at anchored FADs and buoys, industry collaboration in recent years of the Pacific Tuna Tagging Programme (PTTP) have allowed extensive effort for tagging of fish at drifting FADs (PTTP Report 2019, SC15-RP-PTTP-02), which constitute the vast majority of FADs in the WCPO.

Oceanographic conditions affect tropical tuna distributions at broad scales (Senina et al. 2018, Rouyer et al. 2010, and Lehodey et al. 1997), but their effect on individual and school behaviours are harder to ascertain due to the inherent difficulty of *in situ* experiments. Diving behaviour of free-schooling bigeye appears to change in relation to longitudinal changes in the thermocline depth (Abascal et al. 2018), while there is some evidence that associative-type behaviour is more common in a sample of yellowfin tuna electronically tagged around the Bismarck and Solomon Seas (Scutt Phillips et al. 2017). One key issue in these types of behavioural analyses is the lack of accuracy of light-based geolocation methods from archival tags (Leroy et al. 2013), which in general only permits inference to be made regarding large scale longitudinal movements, particularly in equatorial zones. This prevents meso- and fine-scale examination of behaviour in response to environmental conditions due to the inability to link recorded behavioural data to a specific location. Acoustic telemetry (sonic tagging) bypasses this inaccuracy by transmitting data from the tag to a receiver, the position of which is known, allowing recorded behavioural data to be linked to a specific position within a radius of around 0.5km of the receiver. The compromise in this tagging strategy is that, once a fish is out of range of an acoustic receiver, no data is gathered regardless of whether that individual is recaptured and the acoustic tag returned or not.

This project aims to expand significantly the number of electronic tags released on drifting FADs in the WCPO. New data were obtained via the release of fish tagged with acoustic transmitting 'sonic' tags, capable of transmitting presence and depth information to an acoustic receiver attached to the drifting FAD of release, which is then transmitted via satellite in real-time. The release of archival tags also augments the current database of electronic tag information collected as part of the PTTP, although due to the need to recapture these fish, there exists a necessary delay in archival tag data retrieval. By examining the behaviour of bigeye (and where possible yellowfin) tuna whilst associating with FADs, and identifying any changes in response to oceanographic and other environmental variables, the possibility for potential mitigation measures to minimise the catch of small individuals of these species is discussed.

This paper presents the first review of the data obtained by the project during the PTTP CP13 tagging cruise (PTTP Report 2019, SC15-RP-PTTP-02). This consists of presence and depth data from bigeye, yellowfin and skipjack tuna tagged with acoustic telemetry tags at receiver equipped 'listening' FADs. We summarise the data in the context of FAD residence times, movements and depth distributions, and take an integrated analytical approach by combining oceanographic, fisheries, and biological information to explore potential drivers of these behaviours for bigeye tuna. We discuss preliminary results in the context of bycatch mitigation for small bigeye catch and future use of tagging data.

3. Tag Deployment, Data and Methods

The total number of sonic tag releases during CP13 was 179, providing individual behavioural data for 1846 days from 86.6% of the fish tagged (Table 1). The majority of fish were caught at night using rods and reels using heavy metallic jigs, with fewer fish caught during the day by the dangler/trolling technique. The research area was located between 166°41'E to 178°13'W, and 5°42'S to 3°11'S, and tagged fish fork lengths (FL) ranged from 37 to 98cm (distributions shown in Figure 1), from mid-July to mid-August 2018. Fish were tagged by surgical insertion of Vemco V13P sonic tags, as described in Leroy et al. (2007), whilst associated with one of eight drifting FADs, all of which were also equipped with Vemco VR4 acoustic listening buoys, capable of remotely transmitting data from detected tags via satellite and providing an associated position estimate from triangulated satellite signals. Seven of these FADs were also equipped with satellite echo-sounder buoys, which remotely transmit information on the position and the estimated biomass of the target species (in this case skipjack tuna) associated with the FAD. The lone FAD with no echo-sounder buoy, CP13-DF5, was one of two lost or abandoned FADs found during the cruise. Sonic tagged fish were released on both this FAD (178°0'E 5°32'S), and a nearby, echo-sounder buoy equipped FAD, CP13-DF6 (177° 58'E 5°34'S), over a four-day period. There was considerable switching between these two FADs by sonic tagged fish within the same period of residence, and here we refer to these tag releases as 'double FAD' releases. The six remaining FADs were identified through support and collaboration with the Tri Marine Group. No anchored FADs were equipped with acoustic receivers as part of this project, and so here our use of the acronym FAD refers to drifting FADs.

In addition, a number of 'double-tagged' fish, implanted with both archival and sonic tags, were released during CP13. As only two of these tags have been caught and returned, we do not include their analysis here. More detailed information regarding the CP13 cruise, including stand-alone analysis of these double-tagged fish, can be found in the most recent PTTP report (PTTP Report 2019, SC15-RP-PTTP-02).

Table 1. Summary of data collected from CP13 sonic tag releases

Species	No.	Data reported	Percentage	Second receiver data	Percentage	Total days of data	Mean days of data per tag
Bigeye	108	97	89.8	13	12.0	1258	11.6
Yellowfin	57	45	78.9	3	5.3	529	9.3
Skipjack	14	13	92.9	0	0.0	59	4.2

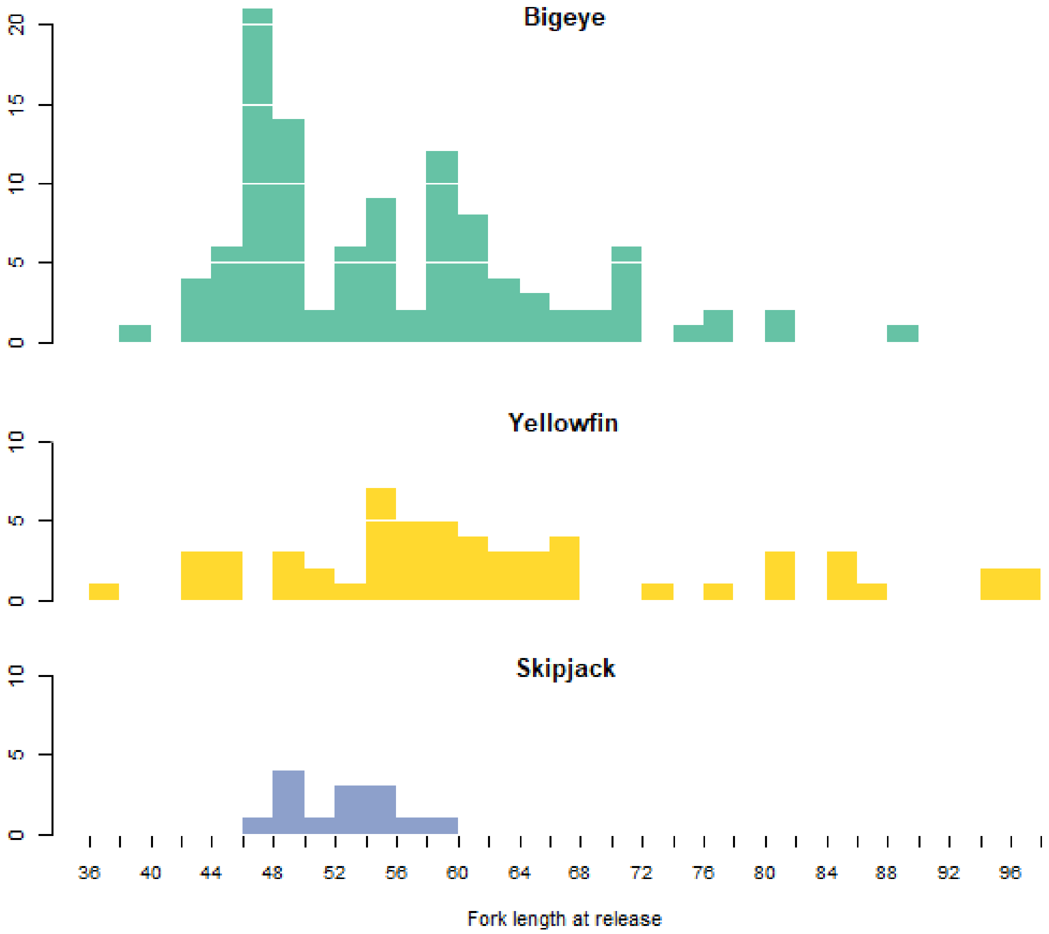


Figure 1: Length at release distributions for CP13 sonic tagged fish

Data collected by these sonic tag releases consist of a series of detections and associated depth information, at around three minute intervals, whenever an individual is within the detection radius of the acoustic receiver. As all release FADs were equipped with either satellite or VR4 buoys that transmitted position, the trajectory of the FAD, and therefore any detected fish associating with that FAD, can also be tracked. Such data can be considered at both an individual level (Figure 2), or at the school level (Figure 3).

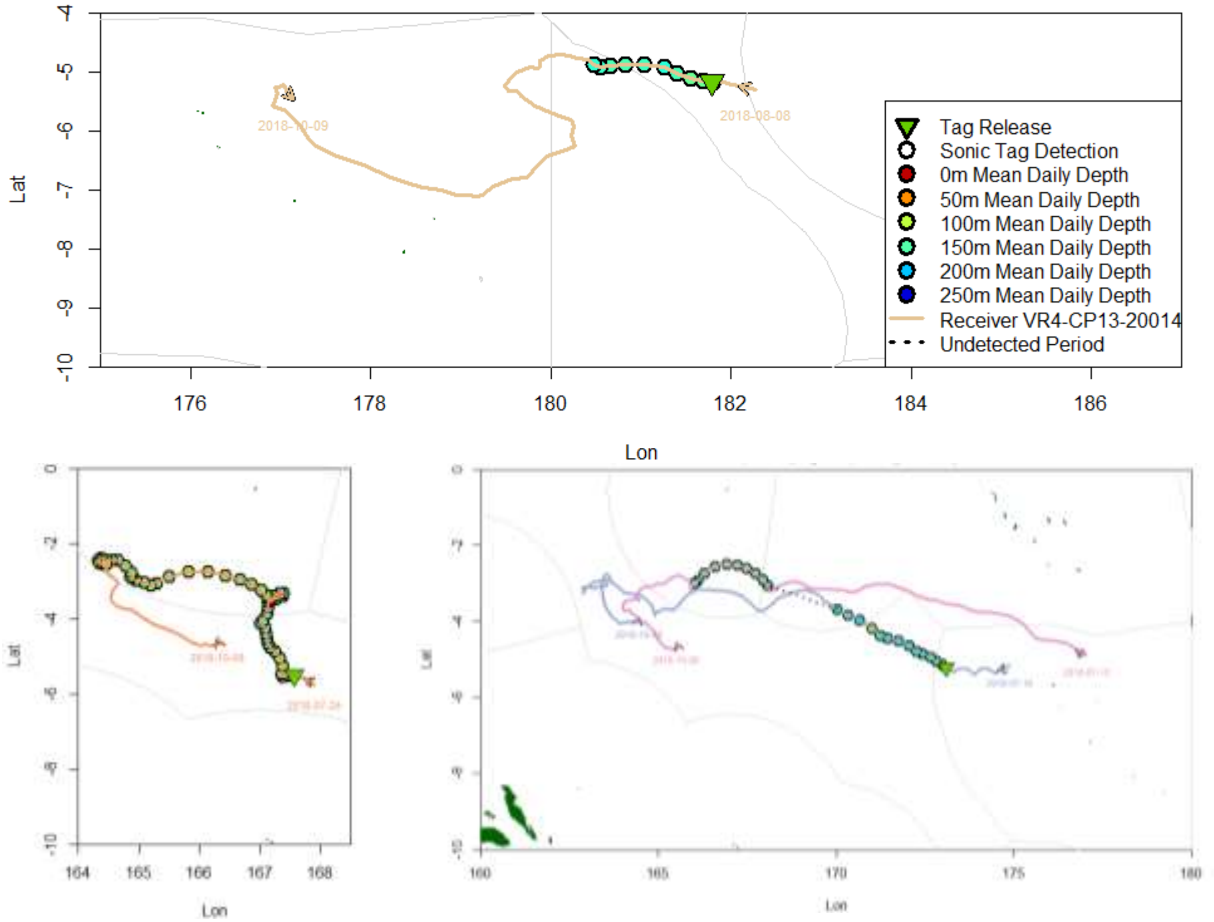


Figure 2: Examples of three individual fish association events across four separate FADs: a 62cm FL bigeye tuna (top); a 60cm FL yellowfin tuna (bottom left); and a 56cm FL bigeye tuna that associated with two separate receiver equipped FADs whilst at liberty (bottom right).

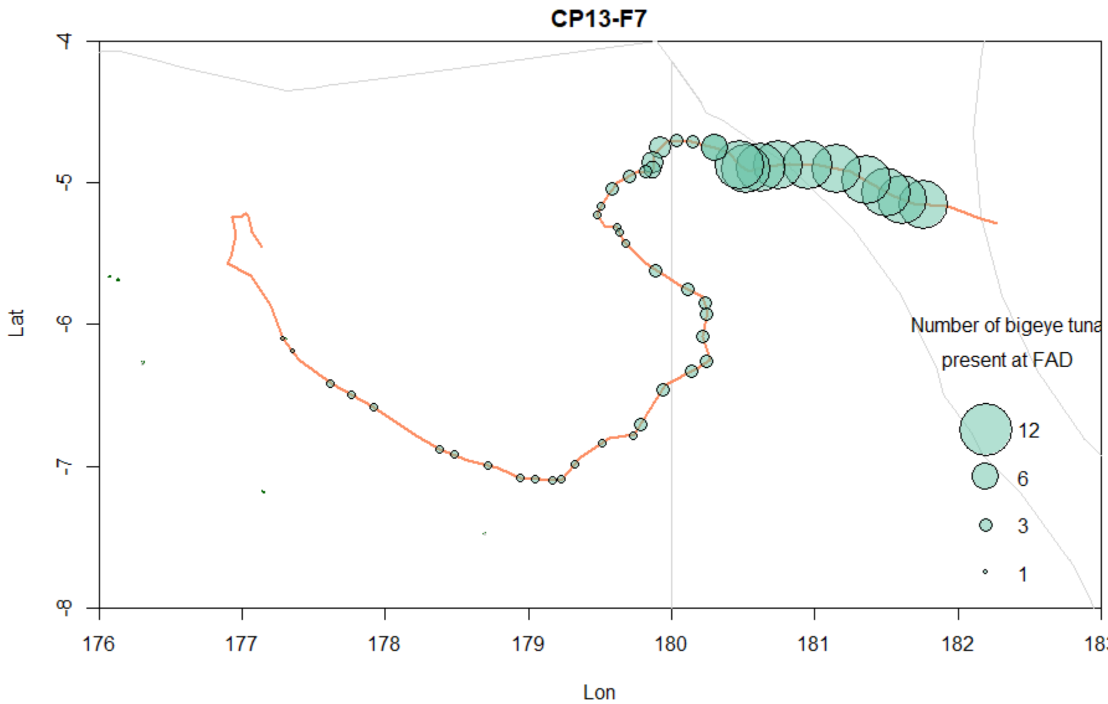


Figure 3: Example of the change in total number of sonic tagged fish associated with FAD CP13-F7 during its drift trajectory, (accessible via http://www.spc.int/webtagging).

Behavioural data from each sonic tagged fish were summarised by dividing the transmitted detection data into distinct association event periods, and calculating summary metrics over daily or sub-daily scales. Each of these association events were determined using a formula for continual residence time (CRT). Used in many previous studies of tuna behaviour, CRT is defined as the period during which sonic tagged fish are associated with a floating object, and do not leave the detection radius of the acoustic receiver-equipped FAD for more than 24 hours in one period (Matsumoto et al. 2016; Capello et al. 2016; Robert et al. 2013; and Dagorn et al. 2007). Any further association event with a receiver-equipped FAD after a continual absence of more than 24 hours was treated as a separate association event with a new CRT. When fish were present at two FADs during the same period of associative behaviour, as occurred several times during the 'double FAD' event, these were treated as a single residence, with a single CRT.

In addition, finer-scale, within-day residence behaviours were examined. To examine day-time and night-time presence at the FAD, the number of hours during which individuals were detected at least once were separated into day and night periods. Timings were identified based on nautical dawn and dusk periods calculated using the angle of the sun to an observer at the location of the FAD on the day in question. In addition, we determined whether fish were present during the pre-dawn period between the visual disappearance of stars in the sky and first light, a period of around 30 minutes when most FAD sets occur, using a similar method. Finally, mean depths of the tagged fish during all these periods were calculated, using the depths transmitted from the Vemco V13P sonic tags.

These summary metrics were calculated for each dawn-to-dawn day that the fish was present at a receiver equipped FAD, and linked to a mean longitude and latitude position given by either the echo-sounder buoy or, if not present (one FAD: CP13-DF5), the triangulated position of the VR4 acoustic receiver. Using this date-position information, a number of environmental and other covariates were collected and coupled to the behavioural data summarised during each FAD association event by each fish. Environmental covariates examined in this report are:

- *Lunar illumination*. Calculated as a proportion of the moon face illuminated by the sun, from zero (new moon) to one (full moon).
- *Sea surface temperature (SST)*. Taken from the NOAA Global Blended SST Analysis, using 'observed' temperatures via interpolated remote sensing. Data were available at daily, ¼° resolution, and further explored using re-aggregated fields at ½° and 1° resolution.
- *Change in sea surface height (∂SSH)*. Calculated from the HYCOM + NCODA analysis, available at daily, 1/12° resolution. Data fields where then resampled at ¼°, ½° and 1° resolutions, before the first-order partial differentials were calculated, using central differencing with forward- or backward-differencing at the domain limits of the edges of land. This gave two fields: *∂SSH/dx* the longitudinal change in SSH, and *∂SSH/dy* the latitudinal change in SSH, which can be indicative of eddies, the boundary between two bodies of water, or other meso-scale ocean features linked to changing habitat for tunas.
- *Estimated, resident skipjack biomass*. The daily estimated 'maximum' tonnage of the associated target species present at the FAD, in this case skipjack, calculated by the attached echo-sounder buoy, when available. For tagging during the 'double FAD' event, a Marine Instruments echo-sounder buoy was attached to only one of the two FADs. Given the difficulty in comparing biomass estimates between this type of buoy and the Satlink buoys attached to the remaining FADs in this study, tagged fish on the 'double FAD' experiment where excluded from statistical models that included this biomass estimate (see below).
- *Estimated local dFAD density*. Taken from the preliminary, estimated dFAD densities calculated at daily, 1° resolution, using data from the Parties to the Nauru Agreement FAD tracking programme, combined with ocean-current informed

interpolated trajectories where data were missing (Escalle et al. 2019, SC15-MI-WP-12).

- *Time-at-FAD*. The number of days since the beginning of the association event (or release, in the case of initial associations).
- *FAD Speed*. The mean velocity of the FAD over a 24-hour period of the FAD.

Where covariates were spatially explicit, bilinear interpolation was used to estimate values at the mean absolute longitude and latitude position of the FAD.

Additional time- and space-invariant covariates were also collected for each classified association event:

- *Species*. The three species of tuna were treated separately.
- *FAD of association*. The FAD at which the association event occurred. In the case of initial associations, this can also be considered as representative of the school of release, as all tagging on each separate FAD occurred within 48 hours.
- *Length at release*. The fork length of the individual, at release.
- *Stomach fullness*. Stomachs from biological samples taken from fish of the same associated school during tagging events were examined and assigned a fullness coefficient. The mean of this coefficient was associated with each fish from the same release event.

Behavioural metrics calculated from sonic tag data from bigeye tuna were used as the response variable in a series of statistical general additive modelling (GAMs) exercises, with the above covariates explored as possible explanatory terms. Models were developed on two sets of data, each derived from the residence information obtained from the each sonic tag association event (i.e. each CRT).

First, the behavioural data for each day of association from each bigeye tuna were considered as independent observations in models, which were then fitted to corresponding covariate data. Daytime, night-time and pre-dawn presence were modelled as a binomial response to environmental covariates. Daytime and night-time mean depth were also modelled as normally-distributed response variables to these environmental covariates.

Second, the number of departures of all tagged fish at each FAD, each day, were considered as response variables indicating abandonment of the FAD by bigeye tuna. In this case, each data point represented the number of fish departing and remaining at a FAD on a given day, and was modelled as a binomial response to explanatory, environmental covariates shared by all fish at the FAD on that day (table 2).

Table 2. List of bigeye tuna behavioural GAMs estimated during this study

Variable	Observations	Temporal period	Assumed Response
Presence at FAD	Number of hours during which each fish was detected at the FAD at least once, each day/night	Day time	Binomial
		Night time	
	Binary true/false of detections by each fish, each dawn	Pre dawn	
Mean Depth	Mean depth obtained from all sonic tag transmitted depth data whilst fish were associated with the FAD	Day dawn	Normal
		Night time	
		Pre dawn	

Departure	Number of tagged fish departing and remaining each FAD, each day that tagged fish were present	Daily	Binomial

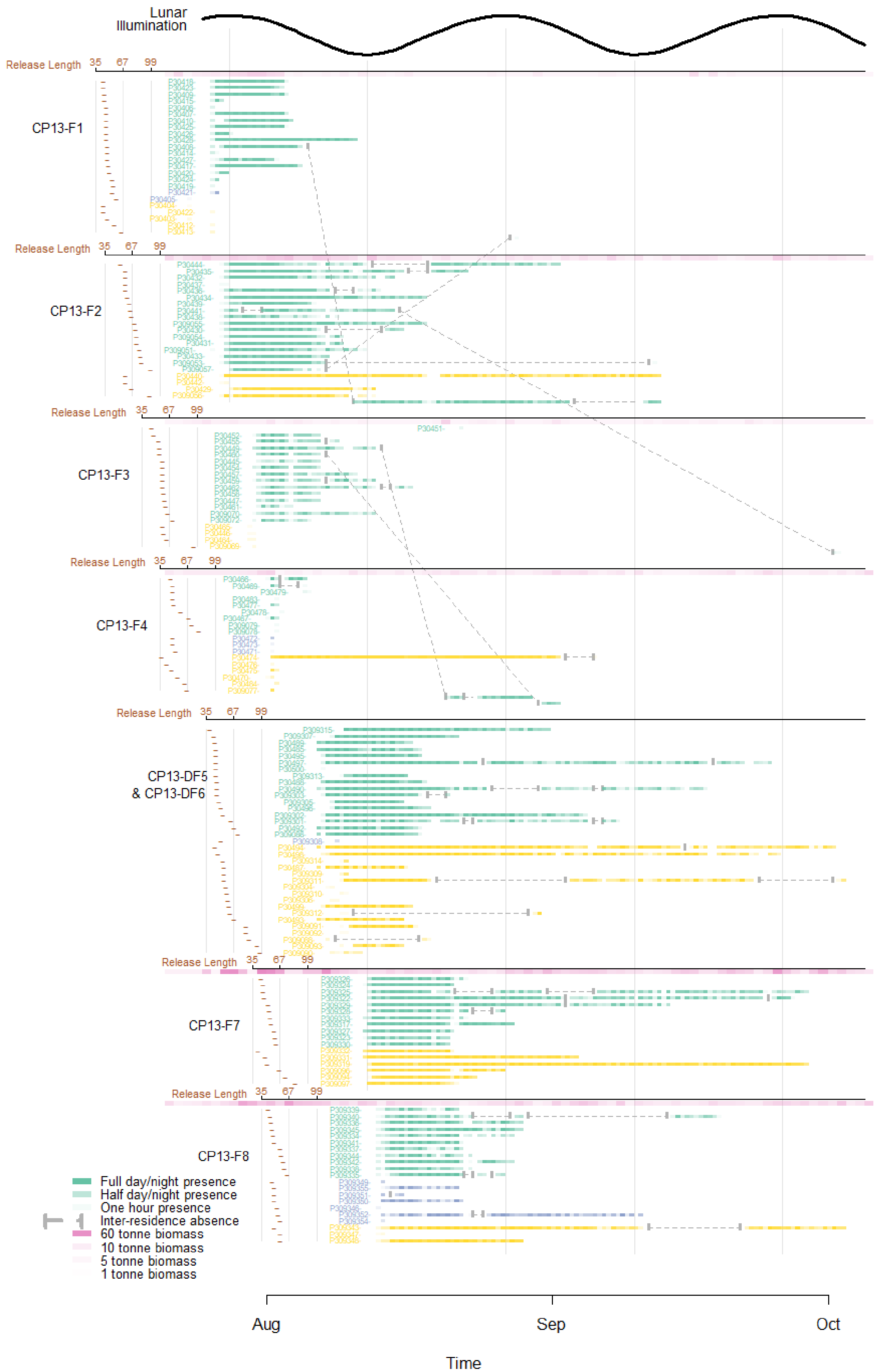
Preliminary statistical models were fitted to observations from the sonic tagged bigeye tuna to examine the potential effect of environmental covariates on depth distributions and presence/absence behaviour. Generalised additive models (GAMs) were used to allow for non-linear effects of covariates on response variables. Logistic regression models were fitted to the presence/absence of individual bigeye tuna at FADs, with separate models for daytime, night-time and the pre-dawn period. An additive regression model assuming normal errors was used for daytime and night-time mean-depths of individual bigeye. Finally, logistic regression models were also fitted to the proportion of bigeye departing a FAD each day. Penalised splines were used where necessary to examine potentially non-linear effects on response variables. A model reduction approach was used to determine which covariates to include in the model, taking account of the significance of terms and AIC, and multi-collinearity between potential covariates (e.g. partial differentials of the same spatial oceanographic variables). Error distributions allowing for over-dispersion were explored (e.g., beta binomial), although these did not improve model fit.

4. Analyses

An overview of all sonic tag detections from experiments carried out during CP13 is given in Figure 4, ordered by release event dates, species and FL at release, alongside several time-varying covariates and movements between FADs. Clear patterns in school cohesion can be seen, including many individuals leaving the FAD at the same time (e.g. almost all tagged fish on FAD CP13-F4), or making sub-24-hour excursions during the same half-day period (e.g. bigeye tuna released on FAD CP13-F3). When individuals remained at a FAD, despite many other tagged fish departing simultaneously, the smaller yellowfin tuna often remained behind (e.g. FAD CP13-F4).

Residence times

Of all the sonic tagged fish during CP13, the percentage exhibiting association events with an acoustic receiver equipped FAD was 90% for bigeye tuna (97 fish), 79% for yellowfin (45 fish), and 93% for skipjack (13 fish; table 1). The length of residence times during separate association events varied both among association events and among species (Figure 5). Overall, median CRTs were longest for bigeye tuna (10 days), with much shorter median CRTs for yellowfin (2 days) and skipjack (1 day). When considering only the first association event following release, this was generally longer for bigeye tuna (11 days), and comparable for yellowfin (2 days) and skipjack (1 day). However, when this first event was excluded from those fish who exhibited two or more subsequent association events with a receiver equipped FAD, CRTs were much shorter for bigeye tuna (median = 3 days), again comparable for yellowfin (median = 2 days) and much longer for skipjack (median = 10 days). It should be noted that the number of yellowfin and skipjack exhibiting a second association event was very low, only six and two fish, respectively. Finally, five bigeye tuna exhibited an association event with a FAD other than the one at which they were released, with a median CRT of 3 days, though one fish did associate for 24 days (bigeye P30408 at FAD CP13-F2, Figure 4).



Lunar Illumination
Release Length
35
67
99
CP13-F1
CP13-F2
CP13-F3
CP13-F4
CP13-DF5
& CP13-DF6
CP13-F7
CP13-F8
Full day/night presence
Half day/night presence
One hour presence
Inter-residence absence
60 tonne biomass
10 tonne biomass
5 tonne biomass
1 tonne biomass
Aug
Sep
Oct
Time

Figure 4 (overleaf). Abacus plot of all CRTs following CP13 release events, showing number of hours detected during each half-day or -night period for each fish (horizontal bars). Releases are grouped by release FAD (double FAD releases combined), then species, and finally increasing fork length (red dashes show length for each release). Echo-sounder maximum biomass estimates are shown for each FAD where available (lilac), and lunar illumination overlaid (top). Dashed lines represent continual absences between CRTs, occasionally between FADs.

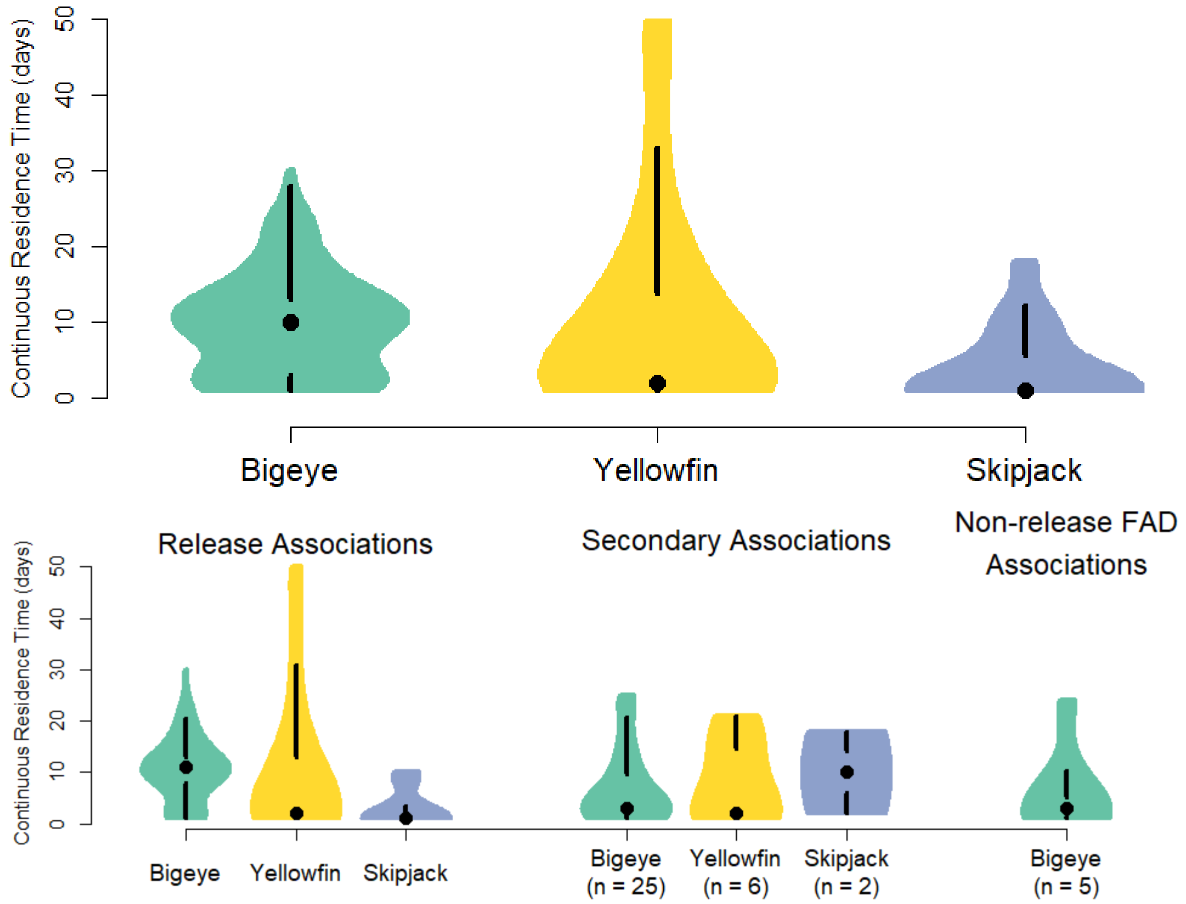


Figure 5. Distribution of detected continuous residence times, across all three tuna species for: all association events combined (top); initial associations following release (bottom left); any association events following that at release (bottom middle); any association events with a FAD other than that on which the fish was released (bottom right).

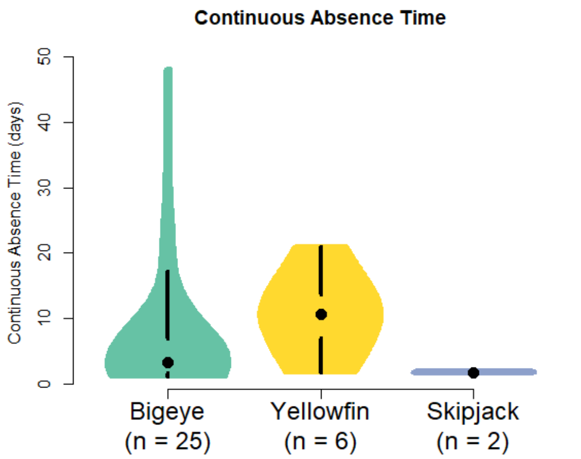


Figure 6. Distribution of all continual absence times.

Continuous absence times

Continuous absence time (CAT) is defined as the length of time between CRTs of individual fish that exhibited multiple residences, and is shown in Figure 6. Most CATs were short for bigeye tuna (median 3.2 days), with the longest being 48.2 days for a 65cm FL fish released on FAD CP13-F2 (figure 4), later re-associating with FAD CP13-F3 for a single pre-dawn period. Observed CATs were longer from yellowfin tuna (median 10.5 days), though only six fish exhibited more than one CRT from which CATs could be calculated.

The maximum CRT was 50 days, exhibited by a 49cm FL yellowfin tuna released at the FAD CP13-DF5 during the double FAD event and associating with both FADs during the initial 10 days, before remaining with FAD CP13-DF6 (P30498, Figure 4). The maximum CRT for a bigeye tuna was 30 days, for a 55cm FL fish, also released at the CP13-DF5 double FAD event, remaining with CP13-DF5 for 10 days before switching residence and remaining at the second FAD CP13-DF6 until day 30. The longest CRT for a skipjack tuna was during a secondary association by a 55cm FL fish, lasting 18 days after a 2 day absence from an initial 10 day association event on FAD CP13-F8.

Stomach fullness

All but three of 52 stomachs sampled from schools during release events were empty, and so given the low sample size and lack of signal, these data were not included in any further analyses. Of note is that of these samples for bigeye tuna, the only school to contain fish with any non-empty stomachs was that at FAD CP13-F4. Sonic tagged bigeye tuna from this school exhibited the shortest CRTs of any school in this study (Figure 4).

Depth distribution

Depth distributions of fish while associating with receiver-equipped FADs over different times of the day are shown in Figure 7. While individual depth observations varied from the surface down to 380m (likely approaching the vertical limit of acoustic detection, given by VEMCO as between 539-282m, depending on conditions), for bigeye tuna depth distribution during the daytime was tightly centered between 138 and 174m (interquartile range). There was overlap in the interquartile ranges of all species during the different times of day, but this overlap was greatest during the predawn period, where all three species exhibited more shallow behavior than during either day or night whilst associating with the FAD.

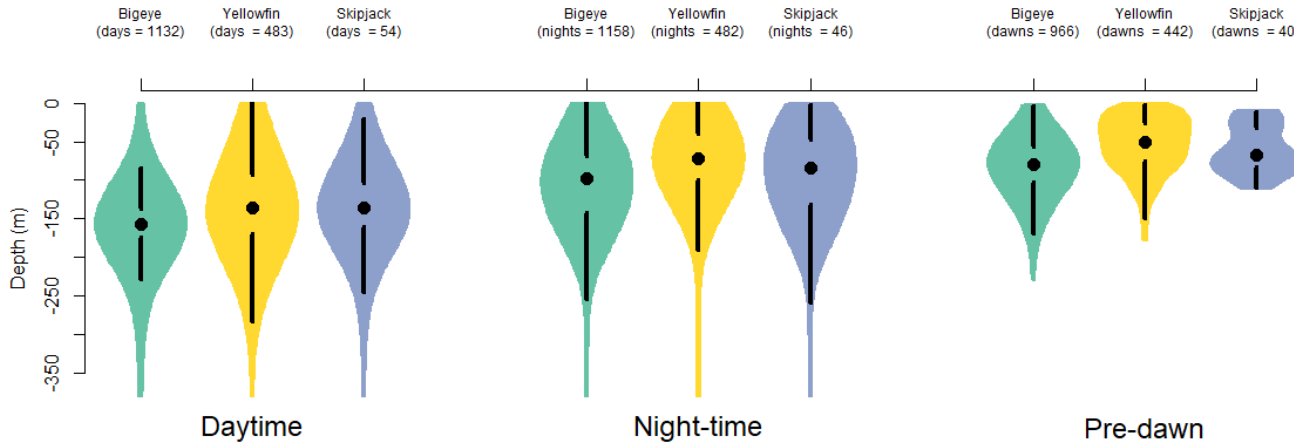


Figure 7. Distributions of all transmitted depth data during different times of the day for all three species of tuna, with the number of distinct day/night/dawn periods providing data. Median values are shown with circular points.

Statistical modelling

Residual diagnostics indicated poor model fits in the case of day-time and night-time FAD residence behaviours, so only the model on presence/absence at pre-dawn is presented here. Models of depth-distribution detected weak effects of covariates on bigeye depths during both daytime and night-time, and are not reported here. However, we note that the FAD of association was a significant categorical term in all models of individual behaviour, highlighting how similar the behaviour was across fish, as most of our data comes from the initial association events of groups of fish. Similarly, the non-linear effect of lunar illumination was clear on all response variables explored, with a strong change in effect at quarter- and full-moons.

Here, we focus on two robust models (i.e. with acceptable residual diagnostics) that may guide future examination of behaviours relevant to the mitigation of bigeye tuna bycatch: presence/absence of individual fish resident at the FAD during the pre-dawn period of typical purse-seine FAD sets, and causes of residence departure (i.e. end of CRT). A summary of these selected models is given in table 3.

The probability of pre-dawn presence by individual fish each day was modelled as a binomial response to lunar illumination, the local FAD density, FAD of assocation and SST. The FAD of association was only significant for bigeye tuna associating on CP13-F8, the last release event of CP13 (figure 4), with fish on this FAD having a generally lower probability of presence during the pre-dawn period. Lunar illumination had a non-linear effect, with lower probability of pre-dawn presence around new moon, and higher at quarter- and three-quarter to full-moon periods. Higher probability of presence at pre-dawn was associated with relatively lower SST values, between of 28.5 to 29.5° C. Finally, increases in the estimated local FAD density increased the predicted probability of presence at a FAD during the pre-dawn period. Linear predictor effects on the logit scale are shown in figure 8.

The probability of departure from a FAD was modelled as a binomial response to lunar illumination, the echo-sounder estimated maximum biomass of skipjack associated with the FAD, the absolute change in sea surface height longitudinally at ½°, and SST at ¼° resolution. Lunar illumination had a slight effect on probability of departure, being lower during new moon periods. Similarly, relatively higher SST values were associated with slightly higher probabilities of fish leaving the FAD; and larger changes in sea surface height decreased probability of departure. The effect of echo-sounder estimated skipjack biomass was non-linear, showing increased probability of departure when the biomass was less than around 8 tonnes (as estimated by the Satlink echo-sounder algorithm). Linear predictor effects on the logit scale are shown in figure 9.

Table 3. Selected GAMs for examining the effect of covariates on behaviour of bigeye tuna

Response	Model Terms	Generalised R^2	Number of observations
Probability of presence at FAD during pre-dawn period	spline(Lunar Illumination) + factor(FAD of association) + Local FAD Density + SST	0.09	1126
Probability of departure from FAD	Lunar Illumination + spline(Maximum Biomass) + abs(∂SSH/dx) + SST	0.33	170

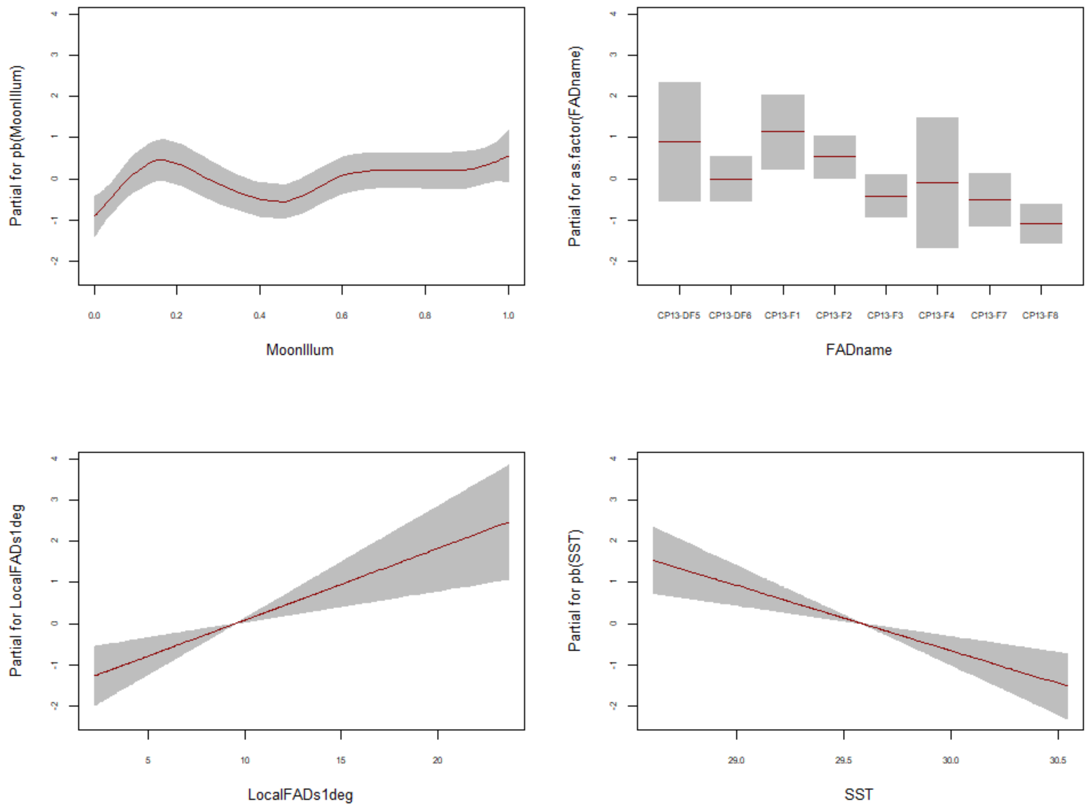


Figure 8. Linear predictor effects in logit space for pre-dawn presence of individual bigeye tuna at FAD. Clockwise from top-left: lunar illumination; FAD of current association; sea surface temperature; and estimated density of local FADs.

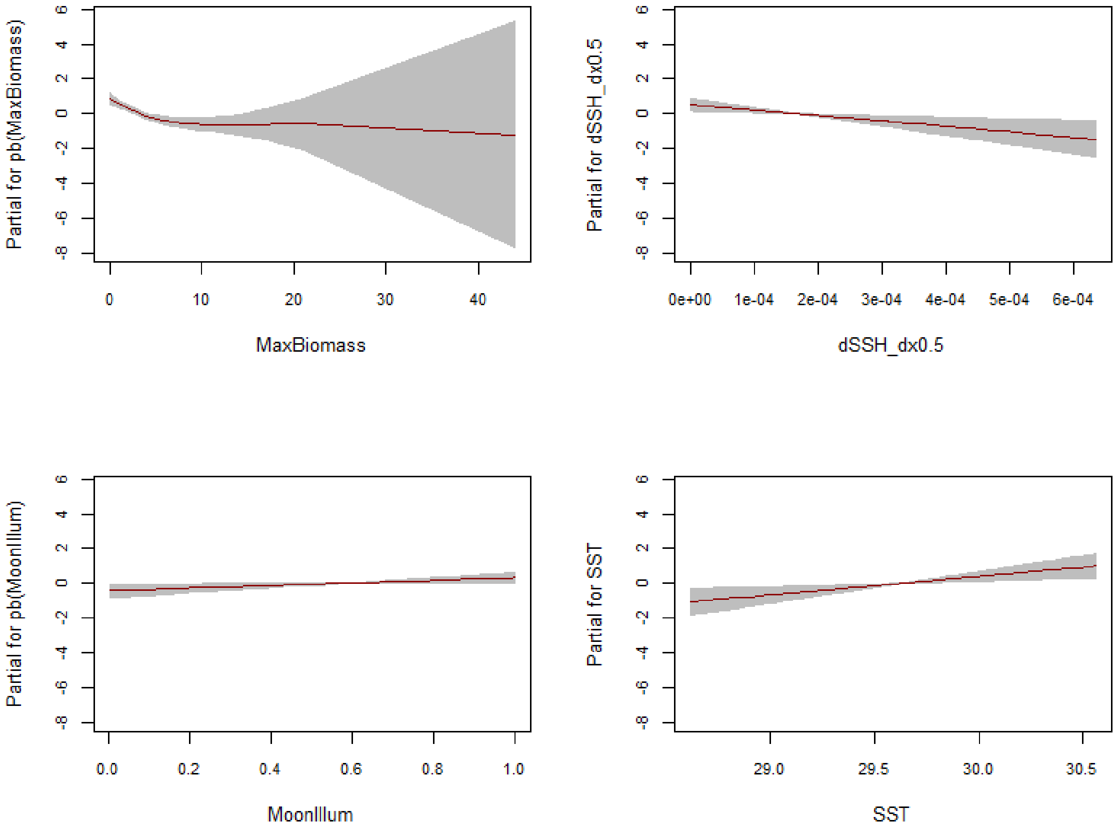


Figure 9. Linear predictor effects in logit space for departure of fish from FADs. Clockwise from left: echo-sounder estimated maximum target species biomass; absolute change in longitudinal sea surface height; sea surface temperature; and lunar illumination.

5. Discussion

The preliminary results presented here add to the growing body of literature regarding the floating object associative behaviour of tropical tunas. Here, we have combined multiple sources of data to build, to our knowledge, one of the most complete pictures that exists of the environmental and school dynamics occurring around drifting FAD-associated tuna aggregations. In the visualisation of the data (Figure 4), the consistently significative effect of FAD during the statistical modelling exercises (e.g. Figure 8), and the apparent effect of estimated skipjack biomass on departure of bigeye tuna; make it clear that school behaviours dominate the dynamics of tagged individuals whilst associating with a FAD. Individuals tend to abandon the FAD at the same time (although they do not necessarily return together) as well as making sub-daily excursions in groups (e.g. on FAD CP13-F3). Many times, FAD abandonment was simultaneous across multiple species, though often smaller yellowfin tuna remained behind to continue association with the FAD. This strong school signal in the data somewhat limits our ability to examine the effect of covariates on these dynamics. Changes to the values of covariates occur simultaneously for all fish released in a given school, within which behaviour was often similar for the majority of initial association events. As only eight schools were considered during this project, expanding our modelling approach to, not only other sonic tagging experiments, but also available archival tagging data from other locations, time-periods and, critically, schools would greatly increase our ability to robustly identity covariate effects on associative behaviour.

The acoustic telemetry experiments undertaken as part of CP13 also allow important validation of previous archival tagging analyses of associative behaviour. The CRTs calculated here are consistent with those estimated previously for bigeye and yellowfin tuna in the region using archival data (Scutt Phillips et al. 2017), which also showed much longer association events following release for bigeye tuna (mean 9.6 days), but shorter association events for yellowfin tuna (mean 5.7 days). Similarly, subsequent association events were much shorter (mean of 2 days for both species), which was also the case in this study. Given the consistency of this observation across multiple studies, we might consider two hypotheses. It may be that that tuna do indeed have multiple FAD-association behavioural modes (Robert et al. 2012), with a longer extended residence that is more frequently encountered during tagging experiments simply due to it constituting a greater proportion of time spent at FADs by tuna. However, it must also be considered that there may be a physiological shock associated with electronic tagging. If indeed, FADs do play an important role in school formation, and even if this 'tagging shock' is not long lived, the duration may be long enough for individuals to miss a departure by their school, and thus be forced wait for a build-up of aggregated conspecifics before leaving. These possibilities should be considered and examined further, given their implication on electronic tagging experiments.

A benefit of acoustic telemetry includes validation of FAD residence during periods of time that are difficult to estimate using archival tagging data (e.g. during shallow night-time behaviour). With sufficient data from sonic tagged fish, it may be possible to train machine learning algorithms or hidden Markov models to identify specific patterns present in vertical behaviour of tunas whilst associated with FADs. Subsequently, these models could classify the likelihood of FAD residence from time-series from archival tagging data, even for night-time and pre-dawn periods. If successful, such an approach would add significant value to existing electronic tagging datasets, and greatly increase the amount of data available to examine fine-scale associative behaviours in the context of bycatch mitigation.

While examination of a greater range of typical environmental variables (such as vertical temperature profile or chlorophyll-α) is planned, the results of preliminary statistical modelling highlight the potential importance of other, non-oceanographic information. Local FAD density in the WCPO has only recently been available as a source of data (Escalle et al. 2019), and the provision of associated echo-sounder information on FADs at which tagging has taken place has further revealed the cohesion of school behaviours across species. Given these school-level behaviours, incorporation of more variables that indicate the state of schools into which tagged individuals are released, must be a priority. While the small number of stomach samples examined here provide little signal, greater numbers and other samples taken during electronic tagging experiments, such as gonad histology, fat content or other fish condition metrics, and isotopic signals from biological samples should all be investigated for their potential to explain the variation in FAD-association behaviour. Local depletion, either through recorded catch data, or even targeted depletion fishing experiments in the local area, would allow some examination of potential density-dependant feedbacks that may drive behaviour and re-colonisation of FADs.

The difficulty in mitigation against, in particular, small bigeye and yellowfin tuna catch during associated purse seine sets targeting tuna, is highlighted by examining the depth distributions of the different species during the crepuscular pre-dawn period. While there exists some variation within individuals and between the species during both the day- and night-time, at pre-dawn, all three tropical tuna species are at their most shallow with the greatest overlap in depth distribution (Figure 7). These results mirror similar studies on drifting FADs in the Indian Ocean (Forget et al. 2015), where a similar overlap was seen between species.

Of more interest is that bigeye tuna were not present at FADs during this pre-dawn period for around 30% all FAD association events recorded in this study. Furthermore, there is some evidence that this presence may be linked to environmental covariates, which should be investigated further. In particular, understanding the apparent effect of increased local FAD density on the likelihood of association-behaviours during these periods could lead to guidance on optimum FAD deployment strategies that minimise bycatch. Similarly, inter-FAD distances, which can frequently be less that 10km from each other within this study area (Escalle et al. 2019), may further explain changes in associative behaviour. Recent studies have similarly suggested that increased local FAD density increases the time spent associating with FADs (Rodriguez-Tress et al. 2017), alongside the possibility of increased school mixing but lower school cohesion (Stehfest et al. 2013). While the results of this project remain preliminary, it may also indicate high FAD density leading to increased school mixing or fragmentation, particularly during night-time foraging, and an increased need for individuals to reform schools around FADs before their vulnerability to predators increases during daylight hours. In such a case, the meeting point hypothesis may be driving the increased vulnerability to purse seine gears through FAD association (Leroy et al. 2013; Fréon & Dagorn 2000). The behaviour exhibited by sonic tagged tuna during the 'double FAD' event undertaken in this study should be examined further in light of this hypothesis. Establishing if these pre-dawn absences by bigeye tuna coincide with presence by target species, in this case skipjack tuna, is crucial for understanding if these environmentally-driven dynamics provide a framework for bycatch mitigation measures. While our simultaneous data for skipjack tuna behaviour is limited in this project, of note is that recent analyses of purse seine bigeye tuna catch in the WCPO suggest increased catch during quarter moon periods (Escalle et al. 2019), the period during which our preliminary analyses also suggest a strong increase in pre-dawn presence at FADs by this species. In contrast, no significant effect of lunar phase was found for skipjack tuna catch, potentially indicating a disconnection between environmentally driven behaviours during this period for these species, when tuna are most exposed to purse seine gears.

An integrated approach is required to find solutions to complicated issues that involve the small-scale ecology of these species, such as in bycatch mitigation. Incorporating data from across commission and member projects, including the Pacific tuna tagging programme (PTTP, SC15-RP-PTTP-02), tissue bank programme (Project 35b, SC15-RP-P35), and data provided by valuable collaborations with the Parties to the Nauru Agreement and the fishing industry (Escalle et al. 2019), will provide such an approach.

6. Recommendations and Further Work

Electronic tagging datasets in the PTTP provide the highest resolution behavioural information on tropical tuna in the WCPO. This project, with a focus on gathering as much local data as possible during the residence of bigeye tuna at drifting FADs, sheds light on the cohesion of school-level behaviours across FAD-associated bigeye and skipjack tuna, and identifies some of the potential drivers for their dynamics. Expanding the statistical power of these preliminary analyses with data across more schools and a greater variety of environmental conditions is important. This might be achieved through further sonic tagging experiments, or by incorporating comparable behavioural metrics estimated from archival tagging data, such as time of departure from FAD of release.

Potential further research includes:

- Examining the effect of other oceanographic covariates on behaviour recorded by sonic tags (e.g. thermocline depths),updated local FAD density data, and inter-FAD network distances, where available;
- Examine further the models of day-time presence and depth distributions, which may indicate further bycatch mitigation through day-time FAD sets;
- Expansion of sample size by including previous, smaller scale sonic tagging experiments, and data from archival tag returns where it is possible to do so;
- Building classification algorithms (e.g. machine learning, hidden Markov models) trained on sonic tagging data to identify pre-dawn, or other FAD-association behaviours important to bycatch mitigation, from existing archival tagging data;
- Examine the potential for sonic tagging to provide fishery-independent mark-recapture and population survey-like information; and
- Integrating analyses of biological samples available from the WCPFC tissue bank, taken from schools in which electronic tagged fish were release, to further build a picture of school condition on FAD-associative behavioural dynamics.

We invite WCPFC-SC15 to:

- Note the preliminary results of this project in the context of identifying potential measures for mitigating against bycatch of undersized bigeye tuna, including the further evidence of high inter-species mixing during typical pre-dawn purse seine set timing and the potential effect of local FAD density;
- Note the value of sonic tagging experiments undertaken in 'arrays' of drifting FADs, and their potential to quantify school mixing, local drivers of behaviour, and provide fishery-independent movement data;
- Note the importance of integration across regional projects and programmes to construct a complete picture of the environmental context of observed behaviours; and
- Note the critical importance of continued collaboration with industry and sub-regional partners to undertake effective electronic tagging and integrated analyses.

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