SCIENTIFIC COMMITTEE
FOURTH REGULAR SESSION

11-22 August 2008
Port Moresby, Papua New Guinea

MONITORING HOOK AND CATCH-AT-DEPTH PROFILES AND APPLICATION OF A HABITAT-BASED CPUE STANDARDIZATION IN THE AUSTRALIAN EASTERN TUNA AND BILLFISH FISHERY

WCPFC-SC4-2008/ME-WP-4

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Monitoring Hook and Catch-at-Depth Profiles and Application of a Habitat-based CPUE Standardization in the Australian Eastern Tuna and Billfish Fishery

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1. Introduction

Assessing the status of the tuna and billfish resources which occur within the Australian Eastern Tuna and Billfish Fishery (ETBF) remains difficult due to the fact that many of the species taken in this fishery are part of single stocks which occur throughout the broader western and central Pacific Ocean (WCPO). Due to this situation, it is not possible to undertake a "stock assessment" on only that portion of the stock which occurs off eastern Australia unless one has an understanding of movement rates of fish into and out of this region. While stock-wide assessment models have been developed for the principal tuna species in the WCPO the results of these assessments still remain uncertain and due to uncertainties in the spatial distribution of both the resource and patterns of recruitment, it remains difficult to infer from these assessments the status of a portion of the resource in a limited region such as off eastern Australia.

Given this situation, in the Resource Assessment Group for the ETBF has recommended that appropriate performance indicators, based on the monitoring of temporal and spatial changes in catch rates and the size of fish caught, be used to monitor the resource status and the success of fisheries management in the ETBF. The need to develop robust empirical-based indicators for monitoring resource status has also been given increased importance with the adoption of a CPUE and size-based harvest strategy in this fishery (Campbell et al 2007).

If unbiased indicators of resource status are to be developed, it will be necessary to develop a better understanding of those factors, apart from resource availability, which influence catch rates. For example, studies have shown that factors such as current sheer (Mizuno et al 1999) and gear type (Yano et al 1998) can significantly affect the expected depth at which longlines fish, while the resulting fishing depths can significantly impact on the resulting catch rate (Mohri and Yasuaki 1997). While methods to standardise fishing effort to account for those factors which influence catch rates have been developed and are routinely used as part of stock assessments world-wide, in most instances the success of this exercise is limited by the absence of data on many of these factors. This is particularly the case in a multi-species fishery such as the ETBF, where one needs to know not only whether there have been changes in the effectiveness of fishing gears, but whether there have been changes in the effective targeting of particular species.

In recent years, a number of developments in the ETBF have greatly improved the ability to collect and analyse the data required to characterise the effectiveness of longline effort in the ETBF. In particular:

i) An observer program commenced in July 2003 within the ETBF and provides an ongoing ability to collect verified catch and effort data and other at-sea data (such as information on fishing practices) which until now has not available.
ii) There have been promising advances in the statistical integration of fisher behaviour (their targeting practices and effective depths of longline sets) with data from archival and pop-up tags on fish habitat preferences to standardize longline effort (Hinton and Nakano 1996, Hampton et al 1998, Bigelow, et al 2002, 2003). Put simply, these methods examine the effective fishing depths of longline hooks relative to the water mass, depth, temperature, oxygen etc preferences of the fish they are targeting to standardize the effort unit. However, the approach requires detailed information on the depth distributions of both the hooks fished by longlines and the different species which are caught, and application of this approach is largely constrained by the lack of such data.
iii) Recent advances and use of archival tags (such as the ongoing work on bigeye in the Coral Sea), together with the integration of remotely sensed data and ocean-circulation models, are greatly assisting in our ability to map the spatial habitat of target species.

To build on these developments in 2004 CSIRO purchased a number of longline gear monitors in order to collect and analyse the data on a number of factors which influence the operational effectiveness of longline fishing gears deployed in the ETBF. In this paper we summarise some of the main results from this project.

2. Data Collection

Deployment of the gear monitors by scientific observers on board longline vessels operating in the ETBF commenced in late August 2004 and continued through until May 2007. The initial purchase of gear monitors consisted of 26 Star-Oddi DST Cent-ex Temperature-Depth data recorders (TDRs) and 250 Lindgren-Pitman HT 600 Hook Timers (HTs). Additional TDRs were purchased during the monitoring phase to cover ongoing losses and failures. The gear monitors were divided into two batches so that up to two observers could deploy them at any one time. Suitably weighted TDRs were attached at the end of the branchlines (with the hook removed to avoid bite-offs) and were programmed to record temperature and depth either every half, one, two or three seconds.

In total, TDRs were deployed during 44 trips and on 248 sets while HTs were deployed during 36 trips and on 201 sets. The number of sets where HTs were deployed was less than that for TDRs as HTs were often not deployed in rough seas as they tended to tangle in the mainline. Up to 13 TDRs (mean=8.6) were deployed during any single set and data associated with 2040 TDR-recordings was collected during the life of the project. Between 70-100 HTs were deployed on any single set.

Each observer was requested to record the hook-number that each TDR was attached. The hook-number is the number of the branchline after the previous float. For example, the first branchline after the float has hook-number 1 and the last branchline has hook-number N where N is the number of hooks-between-floats. A listing of the number of TDRs attached to each hook-number within each observed gear configuration for the 2040 TDRs from which a usable data recording was retrieved is shown in Table 1. For many gear configurations the number of observed sets was not

Table 1 Distribution of TDRs from which usable data was attained across the different hook-numbers within each observed gear configuration. (Note, ns = not specified and HN = hook number).

Hook	Gear Configuration (Number of Hooks-per_Float)															
Number	6	7	8	9	10	11	12	13	14	15	20	25	30	32	35	Total
1	88	9	77	1	2	1	3	2	1	5	4	1	16	0	0	
2	85	11	57	1	4	3	1	0	0	0	0	0	9	0	0	
3	83	3	113	1	2	3	4	3	1	0	5	0	4	0	0	
4	96	9	83	1	4	9	1	0	0	2	0	0	5	0	0	
5	73	7	109	2	6	6	4	3	2	0	3	2	16	0	0	
6	81	4	76	1	5	5	1	0	0	0	0	2	5	0	0	
7		6	58	2	4	5	5	0	1	7	5	0	7	0	0	
8			48	0	3	6	0	0	0	0	0	5	6	1	0	
9				2	2	2	3	0	2	0	5	4	5	0	1	
10					1	6	0	0	0	0	0	7	18	0	0	
11						4	2	0	2	0	0	6	8	0	0	
12							0	0	0	0	0	9	10	0	0	
13								0	1	0	0	4	14	0	0	
14									0	0	0	8	26	0	0	
15										0	0	3	54	0	0	
16											0	4	17	1	0	
17											0	6	14	1	0	
18											0	3	3	0	0	
19											0	6	11	0	0	
20											0	2	5	0	0	
21												1	7	0	0	
22												0	6	0	0	
23												0	3	0	0	
24												0	5	1	0	
25												2	4	0	0	
26													3	0	1	
27													1	0	0	
28													4	0	0	
30													2	0	0	
32														1	0	
35															1	
ns	109		212													321
Total	615	49	833	11	33	50	24	8	10	14	22	75	288	5	3	2040
With HN	506	49	621	11	33	50	24	8	10	14	22	75	288	5	3	1719
No. Sets	65	6	90	1	7	8	3	1	1	3	2	13	46	1	1	248
With HN	55	6	71	1	7	8	3	1	1	3	2	13	46	1	1	219
Sampled HNs	6	7	8	8	10	11	9	3	7	3	5	18	29	5	3	

large (sometimes only 1) with usable TDR data from more than 10 sets only available for four different gear configurations (6, 8, 25 and 30 HPF), with these accounting for 214 (86%) of the 248 TDR-related sets. Unfortunately, for 321 TDR deployments the hook-number was not recorded and so these data could not be used in the subsequent analyses. Fortunately, however, the two gear configurations where this occurred (6 and 8 HPF) were also those from which the greatest number of recordings had been collected, and as the usable number of TDR recordings for these two configurations still remained over 500 (with a good distribution across all hook-numbers) this loss did not have a significant impact on the analyses undertaken. This left a total of 1719 TDR recordings from 219 different longline sets for which complete deployment information was also available.

3. Hook and Catch-at-Depth Profiles

3.1 Hook Profiles

To model expected hook depth, the depths recorded by each TDR were stratified into strata of 20m intervals based on the following definition:

$$\text{stratum} = 20*\text{floor}(\text{depth}/20)+10$$

Hence, stratum d corresponds to depths in the range 20(d-1) to (20d-1). Calculating the total time t_{rdpgs} spent by each TDR r within depth stratum d at hook-number p on longline set s having a gear configuration of g hooks-per-float, then the total time spent by all TDRs at hook-position p within set s having a gear configuration of g hooks-per-float within depth stratum d is given by:

$$T_{dpgs} = \sum_{r=1}^{N_{pgs}} t_{rdpgs}$$

where N_{pgs} is the number of TDRs at hook-number p within a gear configuration of g hooks-per-float on longline set s . It then follows that the proportion of time spent within stratum d by all TDRs at hook-number p within set s having a gear configuration of g hooks-per-float will be given by:

$$P_{dpgs} = \frac{T_{dpgs}}{\sum_{d=1}^{N_d} T_{dpgs}}$$

where N_d is the number of individual depth stratum fished by all hooks. If one assumes that the depths monitored with TDRs are indicative of the depths fished by all hooks within the same set then the proportion of time spent within stratum d (P_{dpgs}) will apply to all hooks at hook-number p within set s.

Finally, if one assumes that the sets and hook-depths monitored with TDRs are indicative of all sets and hook-depths across the ETBF then it follows that the proportion of time spent within depth stratum d by all hooks at hook-number p within a gear configuration of g hooks-per-float across all sets is given by:

$$P_{dpg} = \frac{\sum_{s=1}^{N_s} T_{dpgs}}{\sum_{s=1}^{N_s}\sum_{d=1}^{N_d} T_{dpgs}} \quad (3.1)$$

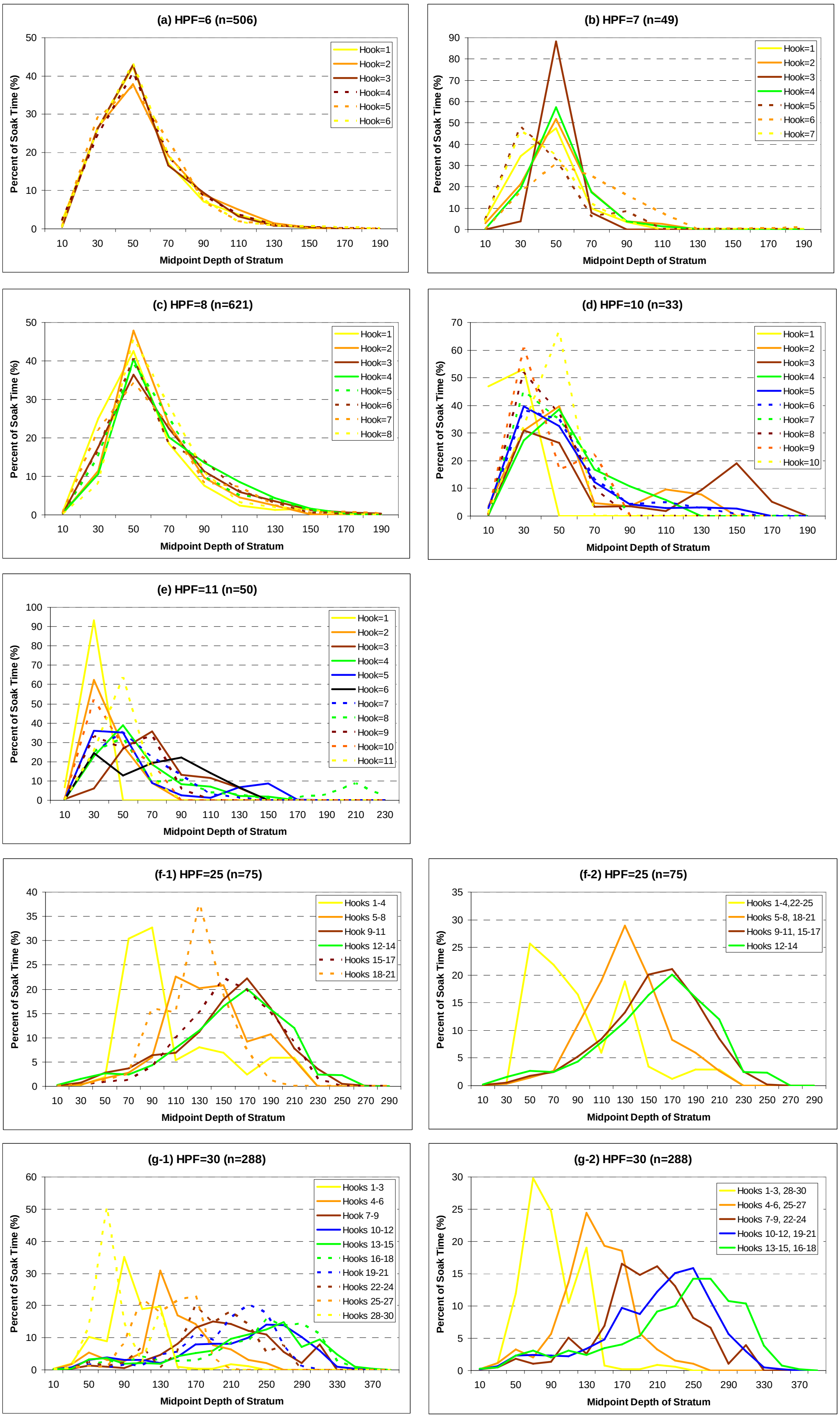
where N_s is the number of monitored sets with g hooks-per-float. Taking the average across all hook-numbers provides an estimate of the mean proportion of time all hooks within a gear configuration of g hooks-per-float spend within depth stratum d:

$$P_{dg} = \frac{1}{g}\sum_{p=1}^{g} P_{dpg} \quad (3.2)$$

The depth-versus-hook profiles, P_{dpg}, are shown in Figure 1 for those gear configurations where more than 30 TDR recordings were obtained. The observed profiles for gear configurations with 6 HPF are seen to be almost identical whilst the profiles for gears with 8 HPF are also seen to be very similar. For gear configurations with 9 or more HPF there is a pattern of hooks closer to the floats generally spending a higher proportion of their time in shallower waters than hooks closer to the middle of the basket. This is expected for lines hanging under the influence of gravity. This is clearly seen in the profiles for gears with 25 and 30 HPF where corresponding groups of hook-numbers a similar distance from either end float have been grouped together (right-hand plots). The mean depths for these five profiles are as follows:

- Hooks 1-3, 28-30) Mean depth = 91 m
- Hooks 4-6, 25-27) Mean depth = 140 m

Figure 1 Mean depth-profile P_{dpg} (percent of total soak time spent within depth strata d) fished by hook-number p within a gear configuration of g hook-per-floats. The number of TDR recordings associated with each HPF, n, is also shown.



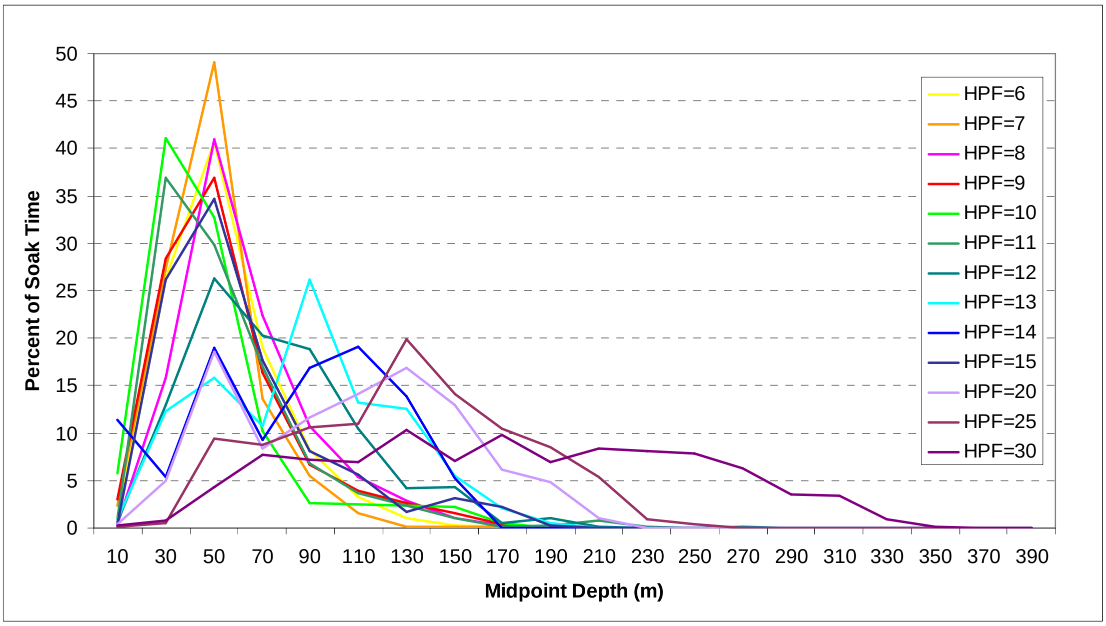
- Hooks 7-9, 22-24) Mean depth = 196 m
- Hooks 10-12, 19-21) Mean depth = 209 m
- Hooks 13-15, 16-18) Mean depth = 229 m

Combining the profiles across all hook-numbers provides an estimate of the mean proportion of time all hooks within a gear configuration of *g* hooks-per-float spend within depth stratum *d*. These estimates are provided in Table 2 and are displayed in Figure 2. Consistent with previous results, all gear configurations with less than 10 HPF are seen to have a similar depth profiles and it is only for gears with 10 or more HPF that the profiles have a successively deeper and greater depth range.

Table 2. Estimated percent of total soak time spent within depth strata *d* by all hooks within a gear configuration of *g* hook-per-floats.

Depth	HPF=6	HPF=7	HPF=8	HPF=9	HPF=10	HPF=11	HPF=12	HPF=13	HPF=14	HPF=15	HPF=20	HPF=25	HPF=30
0-19	1.06	2.37	0.42	3.07	5.71	0.95	0.71	0.95	11.39	0.45	0.42	0.18	0.24
20-39	26.30	27.29	15.86	28.46	41.06	36.87	13.01	12.32	5.39	26.16	4.97	0.56	0.78
40-59	40.73	49.10	40.96	36.86	32.77	29.80	26.31	15.85	18.94	34.67	18.55	9.44	4.32
60-79	19.00	13.67	22.40	16.32	10.23	17.01	20.26	10.68	9.31	17.64	8.33	8.73	7.66
80-99	8.19	5.54	10.69	6.66	2.64	6.86	18.81	26.16	16.92	8.13	11.66	10.58	7.20
100-119	3.23	1.62	5.38	3.94	2.49	3.72	10.44	13.20	19.05	5.68	14.18	10.93	6.91
120-139	1.02	0.07	2.88	2.61	2.35	2.38	4.25	12.54	13.82	1.71	16.94	19.84	10.36
140-159	0.32	0.08	1.00	1.61	2.23	1.02	4.31	5.50	5.20	3.10	12.92	14.18	7.08
160-179	0.09	0.10	0.27	0.40	0.52	0.17	0.54	2.14	0.00	2.22	6.12	10.49	9.81
180-199	0.03	0.14	0.11	0.06	0.00	0.27	1.00	0.56	0.00	0.26	4.89	8.51	6.98
200-219	0.03	0.00	0.02	0.01	0.00	0.80	0.12	0.06	0.00	0.00	1.02	5.30	8.33
220-239	0.00	0.00	0.01	0.00	0.00	0.16	0.01	0.05	0.00	0.00	0.00	0.92	8.07
240-259	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.33	7.88
260-279	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.01	6.33
280-299	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	3.50
300-319	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.46
320-339	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86
340-359	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19
360-379	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
380-399	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Figure 2. Plots of the estimated depth-profiles P_{dg} (percent of total soak time spent within depth strata *d* by all hooks within a gear configuration of *g* hook-per-floats).



3.2 CPUE Profiles by Depth

The hook depth-profiles obtained in the previous section can be matched with the aggregate catch-profile for each hook-number in the set to obtain a catch-by-depth profile for that set. One can then aggregate the catch-at-depth profiles across all sets to obtain an overall catch profile.

However, two problems were encountered in applying this approach to the data available. First, for most TDR-monitored sets not all hook-numbers were monitored and so it was not possible to always match the catch-profile for a specific hook-number with the corresponding depth-profile. Second, the size of the catch for any set is likely to be dependent on the number of hooks deployed. As a different number of hooks were deployed on each set this would mean that the catch-by depth profiles for each set would not be readily comparable unless scaled. In order to overcome these issues, the following approach was adopted. First, the estimated depth-profiles P_{dpg} for each hook-number p within a gear configuration of g HPF as described in the previous section were used. Second, the corresponding nominal catch-rate profiles, C_{pg}, for hook-number p within a gear configuration of g HPF was calculated based on the corresponding aggregate catch and effort across all TDR-sets.

Let N_{pgs} be the number of fish recorded caught on hook-number p within a gear configuration of g hooks-per-float on longline set s and let H_{gs} be the number of hooks deployed on set s. Then the number of hooks deployed at each hook-number on set s is given by H_{gs}/g and the associated nominal catch rate (fish per 1000 hooks), C_{pgs}, on hook-number p is:

$$C_{pgs} = \frac{1000.g.N_{pgs}}{H_{pgs}}$$

The catch rate at hook-number p aggregated over all sets, N_g, with a configuration of g hooks-per-float is then:

$$C_{pg} = \frac{1000.g.\sum_{s=1}^{N_g} N_{pgs}}{\sum_{s=1}^{N_g} H_{pgs}} \qquad (3.3)$$

Combining equations (3.1) and (3.3) gives an estimate of the catch rate within each depth stratum for a hook at hook-number p within a gear configuration of g hooks-per-float:

$$C_{dpg} = C_{pg} P_{dpg} = \frac{1000.g.\sum_{s=1}^{N_s} N_{pgs}}{\sum_{s=1}^{N_s} H_{pgs}} . \frac{\sum_{s=1}^{N_s} T_{dpgs}}{\sum_{s=1}^{N_s} \sum_{d=1}^{N_d} T_{dpgs}} . \qquad (3.4)$$

Aggregating across all hook-numbers, the expected catch rate within each depth stratum for a gear configuration of g hooks-per-float is given by:

$$C_{dg} = \frac{1}{g}\sum_{p=1}^{N_p} C_{pg} P_{dpg} = \sum_{p=1}^{N_p}\left[\frac{1000.\sum_{s=1}^{N_s} N_{pgs}}{\sum_{s=1}^{N_s} H_{pgs}} . \frac{\sum_{s=1}^{N_s} T_{dpgs}}{\sum_{s=1}^{N_s}\sum_{d=1}^{N_d} T_{dpgs}}\right]. \qquad (3.5)$$

For sets with attached TDRs and an associated observer catch data, a summary of the number of sets and hooks, the number of distinct hook-numbers on which fish were observed caught, together with the total number of fish observed caught is provided in Table 3 while the CPUE-by-depth profile obtained for each gear configuration are shown in Figure 3. To provide a better comparison of these profiles across each species the CPUE profiles for each species expressed as a percentage of the total CPUE are also shown (c.f. Figure 3b). Note, in Figure 3b the profiles for swordfish and striped marlin are not shown for gear configurations with 25 and 30 HPF due to the small catch sample (<5 fish in all situations).

Table 3. Number of sets and hooks deployed together with the number of fish observed caught for each HPF gear configuration where usable TDR data was collected.

HPF	Number of Sets	Number of Hooks	Distinct Hook-Num	All Fish	YFT	BET	ALB	SWO	STM
6	65	80,368	6	2883	296	141	553	561	33
7	8	8,858	7	171	15	15	14	56	2
8	87	95,008	8	3275	530	89	290	682	36
9	1	1,050	4	15	1	2	1	4	0
10	7	6,273	10	140	8	16	11	29	2
11	7	6,521	11	201	9	7	15	52	0
12	3	3,422	6	67	18	11	10	6	0
13	1	1,295	6	19	3	5	1	3	0
14	1	1,200	4	10	0	0	0	3	0
15	2	2,318	7	84	0	0	0	0	0
20	3	8,311	10	131	5	46	11	6	0
25	13	21,441	25	2094	229	10	1047	3	3
30	46	77,292	30	4498	240	176	2257	4	3
32	1	2,085	3	5	0	2	0	0	0
35	1	1,700	5	46	3	0	27	0	0
Total	246	317,142		13639	1357	520	4237	1409	79

The CPUE-by depth profiles for each species for the 6 and 8 HPF gear configuration (c.f. Figure 3b) are seen to be almost identical, while the profiles for the different species for the other gear configurations are also seen to be very similar, suggesting that there is little difference in the relative availability-by-depth of these species despite absolute differences in availability (as noted by the absolute differences in the profiles shown in Figures 3a). This result also holds for the deeper longline configurations using 25 and 30 HPF where, unlike the shallower set gears, there are distinct differences in the depth-profiles fished by the different hook-positions. This is somewhat surprising for it is generally assumed that some species have different depth preferences (e.g. yellowfin shallow and albacore deep) and as such one would expect these species to be caught in different hook-positions and consequently have a different CPUE-by-depth profile. Given that the depth-distribution across all hooks in these gears is more uniformly distributed over a greater range of depths, the lack of difference in the CPUE profiles by depth for the different species indicates that the relative distributions of these species by depth is similar.

Figure 3 (a) CPUE by depth and (b) CPUE profile by depth for specified hook-per-float configurations. Note, in (a) the right-hand axis give the CPUE for the ALL fish.

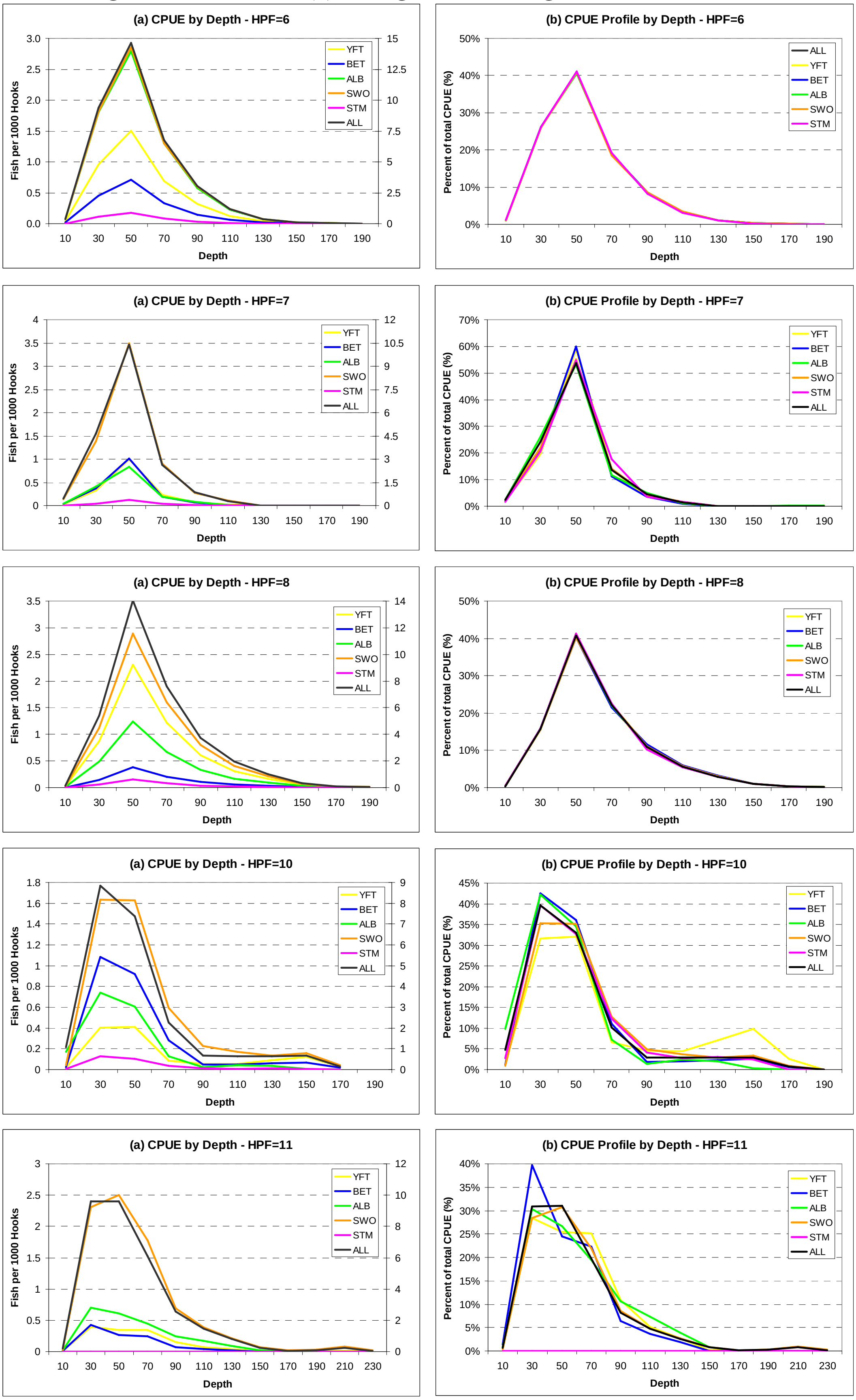
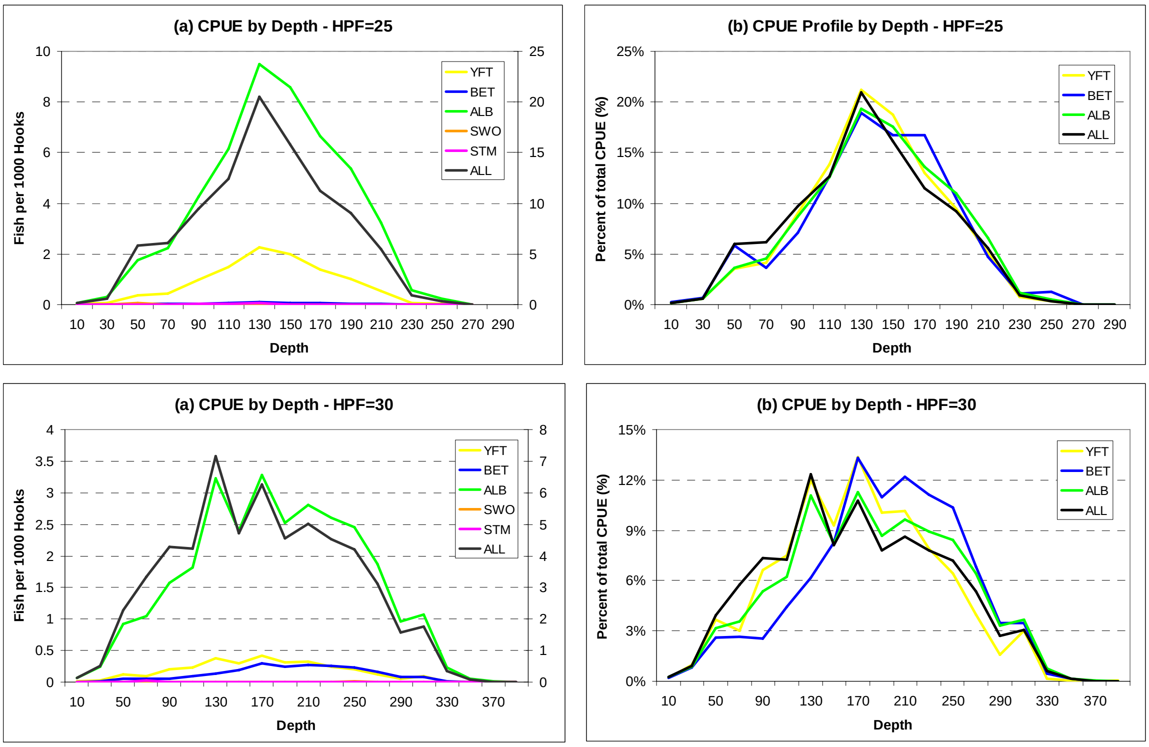


Figure 3 (cont'd). (a) CPUE by depth and (b) CPUE profile by depth for specified hook-per-float configurations. Note, in (a) the right-hand axis give the CPUE for the ALL fish.

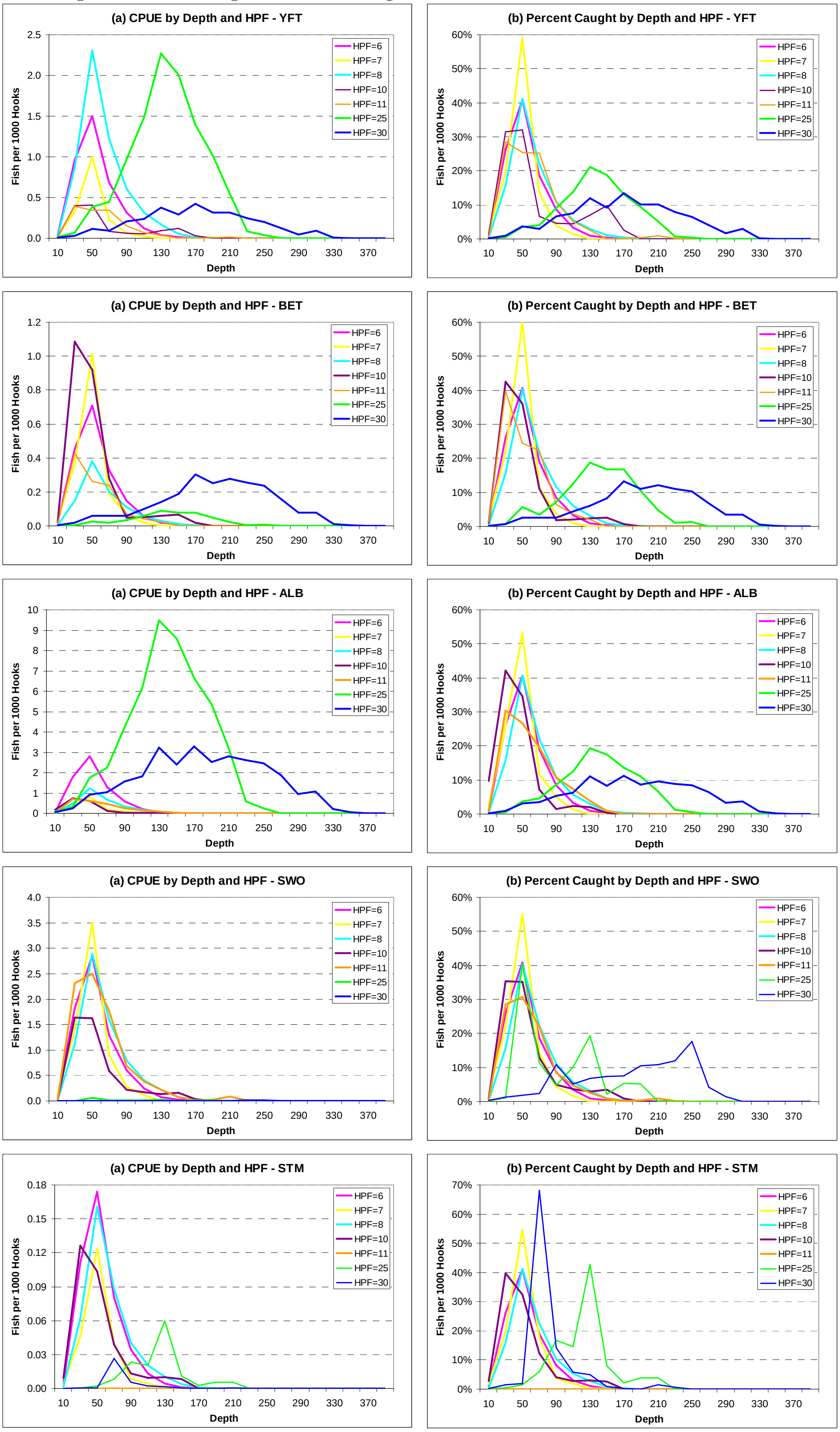


Finally, the CPUE-by-depth profiles for each species across each of the different gear configurations are shown in Figure 4a. Again, in order to better compare these profiles across each gear configuration the CPUE profiles expressed as a percentage of the total CPUE are also shown in Figure 4b. For yellowfin tuna the distribution of CPUE by depth is very similar for sets deploying 10 or less HPF, with the highest catch rates being achieved within the depth interval 40-59m. However, the distributions for those gears deploying 25 and 30 HPF are significantly different. For example, the 65 monitored sets with 8 HPF had a mean CPUE of 2.31 fish per 1000 hooks at depths between 40-59m. This catch rate is seen to be almost the same as the CPUE of 2.27 fish per 1000 hooks at depths between 120-149m for the 13 monitored sets with 25 HPF. While the sample sizes are quite different for these two gears, this result does nevertheless indicate that there can be little consistency in the catch rates of a given species with depth across a fishery the size of the ETBF. The sets deploying 25 HPF were, in general, more than 5-degree further north than sets deploying 8 HPF. Furthermore, it is possible that other factors such as day versus night setting, different seasons of the year may also help explain some of the observed differences in the catch rates of yellowfin tuna with depth.

3.3 Species Availability by Depth

The profile of depths fished by the hooks of any longline gear is far from uniform with the consequence that the fishing power of the longline gear (i.e. the probability of catching a fish in a given time) also varies considerably by depth. If the distribution-by-depth of the target species is given by S_d, then the catch (or catch rate, C_{dg}) of that species by the longline gear within depth strata d will be proportional to S_dP_{dg} where,

Figure 4. (a) CPUE by depth and (b) catch profiles by depth by species across all hooks for specified hook-per-float configurations.



as before, P_{dg} is the proportion of the time spent within depth strata d by all hooks within a gear configuration of g HPF, i.e.

$$C_{dg} = q.S_d P_{dg}$$

where q is some measure of the catchability of the gear. An index of the availability ($q.S_d$) of a species to the longline gear within a given depth stratum d can therefore be obtained by knowledge of P_{dg} and C_{dg}. Furthermore, by dividing this index by the sum of the index over all depth strata fished by the hooks, a measure A_{dg} which is equivalent to the proportion of all fish of that species available to the gear which occur within depth strata d, is obtained:

$$A_{dg} = \frac{C_{dg}}{P_{dg}} \Bigg/ \sum_{d=1}^{N_d} \frac{C_{dg}}{P_{dg}} \tag{3.6}$$

Using the values of P_{dg} and C_{dg} summarised in the previous two sections, indices of resource availability to each of the main gear-types used in the ETBF for several of the principal target species were calculated. (Note, in order to minimise spurious results, for each gear configuration the calculation of A_{dg} was limited to those depth strata where P_{dg} >1%. Gear types were also limited to those where more than 10 sets were sampled.) These indices were then combined to provide a single index, A_d, of availability for each species. This was achieved by scaling the index for each gear configuration by the associated catch rate and for each depth strata dividing by the mean index, i.e.

$$A_d = \frac{1}{N_d} \sum_{g=1}^{N_d} \frac{C_{dg} A_{dg}}{\overline{A}_g}$$

where $\overline{A_g}$ is the mean of the index A_{dg} over all depth strata for which it is defined and N_d is the number of gear-specific indices defined for depth-strata d.

Two sets of indices were calculated. First, the catch rates C_{dg} were set equal to the mean nominal catch rates observed on the associated TDR sets. Second, in order to overcome the limited sample sizes of the TDR sets, the catch rates C_{dg} were set equal to the mean nominal catch rates observed on all related sets deployed in the ETBF during the period that the TDRs were deployed. This assumes that the indices A_{dg} calculated for the TDR sets are appropriate for all sets deployed in the ETBF. The two sets of catch rates are given in Table 4 while the calculated indices are shown in Figure 5 where each index has been scaled so that $\sum A_d = 1$. Scaled in this way, the value of the index equals the proportion of the total population available (down to a depth of 320m) to the gear within each depth stratum.

The two sets of indices display a number of differences. This is related with the fact that there are large differences in the catch rates associated with each gear configuration between the TDR-related sets and all ETBF sets. For example, the highest catch rates of yellowfin tuna for the TDR-related sets were obtained on gears with 25 HPF while for all ETBF sets catch rates of yellowfin tuna decrease across the four gear configurations shown in Table 4. This difference explains the initial increase in yellowfin availability with depth down to around 150m for the TDR-related sets compared to the general decrease in yellowfin availability with depth for the all ETBF sets. Nevertheless, both sets of indices for yellowfin tuna indicate that

Table 4. Number of sets, hooks deployed and associated catch rates for (a) those sets deployed with TDRs and (b) all sets deployed in the ETBF during the period that the TDRs were deployed (August 2004 to May 2007).

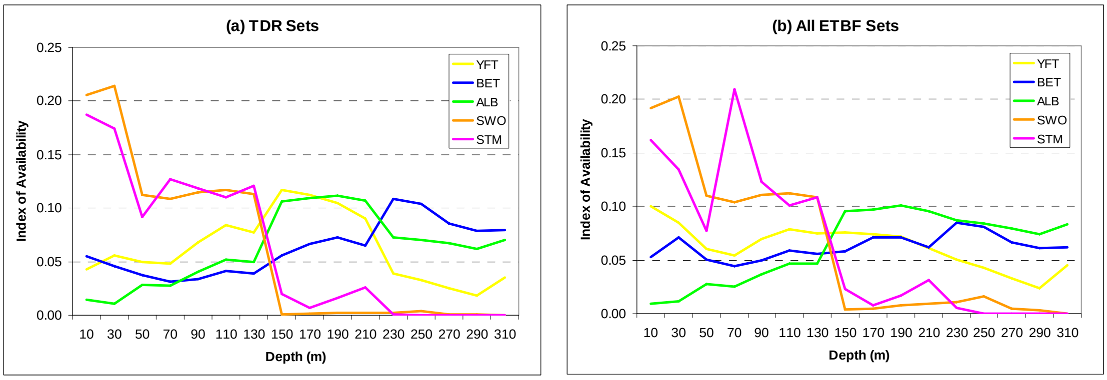
(a) TDR Sets

HPF	NSETS	NHOOKS	YFT	BET	ALB	SWO	STM
6	65	80,368	3.68	1.74	6.87	6.98	0.42
8	87	95,008	5.59	0.95	3.05	7.17	0.39
25	13	21,441	10.72	0.47	48.95	0.14	0.14
30	46	77,292	3.15	2.28	29.17	0.05	0.04

(b) All ETBF Sets

HPF	NSETS	NHOOKS	YFT	BET	ALB	SWO	STM
6	3013	3,113,781	9.51	1.56	4.74	3.85	0.75
8	8171	8,327,567	5.94	2.42	5.99	4.05	0.54
25	228	380,605	5.40	0.98	38.33	0.15	0.30
30	2285	3,835,478	4.49	1.65	37.21	0.14	0.37

Figure 5. Indices of resource availability by depth for the principal target species in the ETBF based on (a) catch rates for the observed TDR sets and (b) catch rates for all ETBF sets during the period that TDRs were deployed (August 2004 to may 2007).



availability remains relatively high (above 5% per depth stratum) down to around 220m.

The results for bigeye tuna also display differences associated with the relative differences in the catch rates between the TDR-related sets and all ETBF sets. Catch rates for the former were highest on the deepest sets (those with 30 HPF) and consequently the availability of bigeye at depths around 230m is more than twice that for depths less than 100m. While availability for the ETBF sets is also highest at depths around 230m, the relative change from shallower depths is not as great. Indeed, the index indicates that availability remains relatively high for all depths down to 320m. The indices for albacore tuna are similar for the two groups of sets and display considerable variation with depth. Availability increases from around 1% in the 0-20m depth stratum to around 10% at depths between 150-200m before declining to some extent. The extent of this decline is smaller for the ETBF sets and as for bigeye tuna availability remains high down to the deepest depth stratum shown.

Apart from some variation in the ETBF striped marlin index within the top 100m (most likely associated with the large variations in the individual gear related indices due to the small number of striped marlin observed) the indices for the two billfish species are seen to be similar for both groups of sets. They indicate that the availability of these species is highest in the top 40m of the water column where around 40% of the total available resource is to be found. Availability then declines to half these levels at depths between 50-130m before dropping to near zero at greater depths.

4 Application of a Habitat-based Method of Standardising CPUE

The hook-depth profiles summarised in the previous section where used to apply the habitat-based-standardisation (HBS) approach to standardising CPUE within the ETBF. The HBS method was developed by Hinton and Nakano (1996) and combines information on the depths fished by longline hooks with information on the spatial and depth distributions of the target species (using information on habitat preference and mapping of this habitat provided by oceanographic models). This method was first applied to Pacific blue marlin before being applied to bigeye tuna in the WCPO by Hampton et al (1998). The method has subsequently been further developed and in recent years has been routinely applied to both bigeye tuna and yellowfin tuna within the context of the stock assessments undertaken for these species within the WCPO (see Langley et al 2005).

4.1 Basic Equations

In order to illustrate the basic approach of the HBS method, consider a volume of water fished by the longline gear during a single set. From the catch equation the number of fish in the catch, C, is related to the total fishing effort, E, and the average fish population density in this volume of water, D as follows:

$$C=qED$$

where q is a fixed constant of proportionality known as the catchability coefficient and is related to the efficiency of the fishing gear. From this equation

$$CPUE = \frac{C}{E} = qD = \frac{qN}{V}$$

where N is the number of fish and V is the volume of water fished.

Now divide this volume into N_d depth stratum each of depth d, cross-sectional area A and volume V. Let N_k be the number of fish within the depth stratum k so that the average density of fish within this stratum is $D_k=N_k/V$. If E_k is the effort (number of hooks) within stratum k, and q_k is the corresponding catchability, then from (1) the catch, C_k, within stratum k is:

$$C_k = qE_kD_k = q_kE_k\frac{N_k}{V}$$

If q_k is considered to be a constant across all stratum then the total catch over all stratum is:

$$C = \sum_{k=1}^{N_d} C_k = \frac{q}{V}\sum_{k=1}^{N_d} E_k N_k$$

Finally, if $E_k=h_kE$ where E is the total effort (number of hooks) deployed and h_k is the proportion of these hooks within stratum k, and $N_k=p_kN$ where N is the total number of fish in all depth stratum and p_k is the proportion of these fish in stratum k, then (3) can be expressed as follows:

$$C = \sum_{k=1}^{N_d} C_k = \frac{qEN}{V} \sum_{k=1}^{N_d} h_k p_k$$

from which

$$CPUE = \frac{C}{E} = \frac{qN}{V} \sum_{k=1}^{N_d} h_k p_k$$

Solving for N provides an estimate of the number of fish in the volume of water based on an observed CPUE:

$$N = \frac{V.CPUE}{q\sum_{k=1}^{N_d} h_k p_k} = \frac{V.C}{qE\sum_{k=1}^{N_d} h_k p_k}$$

Where there are a number of longline sets, S, each having a constant catchability q, this equation can be expressed as follows.

$$N = \frac{V}{q} \frac{\sum_{i=1}^{S} C_i}{\sum_{i=1}^{S} E_i \sum_{k=1}^{N_d} h_{ik} p_k}$$

where h_{ik} is the proportion of hooks in set i which fish within depth stratum k.

If there are T volumes of water each with N_d equally divided depth stratum each of volume V and depth d, but each containing a different number of fish N_j and a different number of longline sets, S_j, then the total number of fish across the entire region can be expressed as follows:

$$N = \sum_{j=1}^{T} N_j = \frac{V}{q} \sum_{j=1}^{T} \left(\frac{\sum_{i=1}^{Sj} C_{ij}}{\sum_{i=1}^{S_j} E_{ij} \sum_{k=1}^{N_d} h_{ijk} p_{jk}} \right) \qquad (4.1a)$$

where: E_{ij} is the number of hooks in the set i in water volume j,
C_{ij} is the number of fish caught in set i in water volume j,
h_{ijk} is the proportion of hooks in set i in water volume j in depth stratum k,
p_{jk} is the proportion of the fish in water volume j in depth stratum k,

Where aggregate data is being used this can be expressed as

$$N = \sum_{j=1}^{T} N_j = \frac{V}{q} \sum_{j=1}^{T} \left(\frac{C_j}{E_j \sum_{k=1}^{N_d} h_{jk} p_{jk}} \right) \qquad (4.1b)$$

where: E_j is the total number of hooks in water volume j,
C_j is the total number of fish caught in water volume j,
h_{jk} is the proportion of all hooks in water volume j in depth stratum k,
p_{jk} is the proportion of the fish in water volume j in depth stratum k,
This equation is similar to that obtained by Hampton et al (1998).

4.2 Initial Application to ETBF

We illustrate the HBS method by applying the basic equations outlined above to the catch of bigeye tuna in the ETBF. This species is chosen as there data available from the archival tagging of bigeye tuna with the ETBF which provides information on the habitat preference of this species within this region. Furthermore, in order to keep this initial analysis simple so that the consequences of changing aspects of the model can be clearly identified and explained, the following simplifying assumptions were made:

1) The ETBF was treated as a single oceanographic entity so that only a single area (or water volume) was required in the analysis. Removing reference to the *j* index in equation (4.1b) above an annual index, I_y, of bigeye abundance in year *y* can be calculated as follows:

$$I_y = \frac{q.N_y}{V} = \frac{C_y}{E_y \sum_{k=1}^{N_d} h_{ky} p_{ky}}$$

   where: E_y is the total number of hooks in deployed in year *y*,
   C_y is the total number of bigeye tuna caught in year *y*,
   h_{ky} is the proportion of all hooks in depth stratum *k* in year *y*,
   p_{ky} is the proportion of bigeye tuna in depth stratum *k* in year *y*.

2) The depth-profile of all hooks deployed in the ETBF is controlled solely by the HPF configuration. Hence, total annual effort E_y can be equated to the sum of the number of hooks deployed within each HPF category, E_{iy}, with each HPF category having a distinctive depth-profile, h_{iky}. Therefore:

$$I_y = \frac{C_y}{\sum_{i=1}^{N_c} \left(E_{iy} \sum_{k=1}^{N_d} h_{iky} p_{ky} \right)}$$

   where N_c is the number of HPF categories deployed in the fishery.

3) The hook-depth profiles, h_{iky}, of each HPF configurations deployed by longline vessels fishing in the ETBF are the same across all years. As such, the *y* index can be dropped from this term.
4) The habitat preference of bigeye tuna, measured by the term h_{ky}, is the same across all years. As such, the *y* index can be dropped from this term.

Based on the above assumptions, the annual index of bigeye tuna abundance can be written as:

$$I_y = \frac{C_y}{\sum_{i=1}^{N_c} \left(E_{iy} \sum_{k=1}^{N_d} h_{ik} p_k \right)} \qquad (4.2)$$

This method was applied for the period July 1997 to June 2007 (i.e. the financial years (FY) 1997/08 to 2006/07) incorporating the following information:

i) Total effort within each HPF category each year, E_{iy}

We used the AFMA logbook data. A listing of the total number of sets deployed during the period FY 1997-2006 for each hook-per-float gear configuration is shown in Table 5. As there was not an TDR-derived depth profile for all HPF configurations

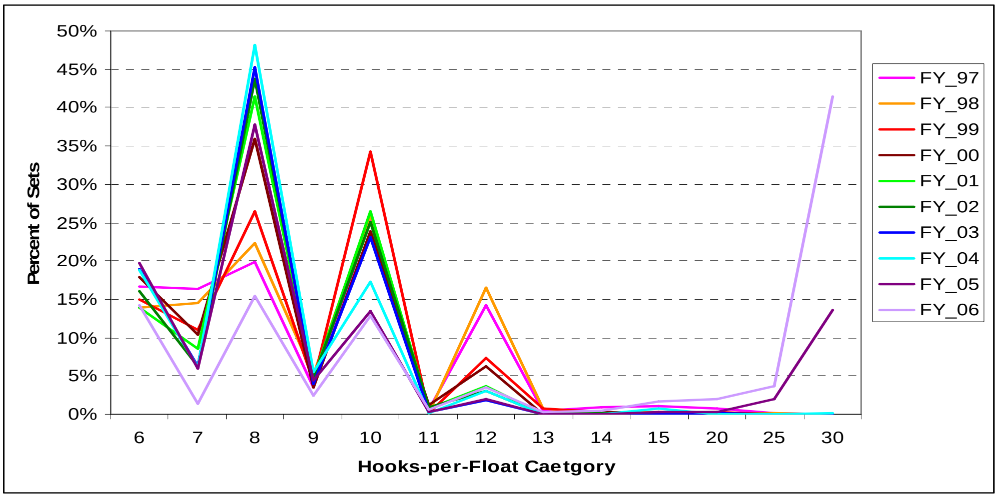
Table 5. Total number of sets deployed during the financial years 1997-2006 by gear setting (hooks-per float). The corresponding HPF setting used in the HBS model is also shown.

HPF Deployed	HPF Marched Profile	Number of Sets	Percent of all Sets
<5	Not Used	366	0.35%
5-6	6	17332	16.36%
7	7	8577	8.09%
8	8	35260	33.28%
9	9	4765	4.50%
10	10	28640	27.03%
11	11	624	0.59%
12	12	5924	5.59%
13	13	237	0.22%
14	14	262	0.25%
15-17	15	482	0.45%
18-22	20	305	0.29%
23-27	25	335	0.32%
28-40	30	2818	2.66%
>40	Not Used	28	0.03%
Total		105955	100.00%

Table 6. Number of hooks deployed each financial year in the ETBF within each of the hook-per-float categories used in the HBS model described in the text

HPF	FY_97	FY_98	FY_99	FY_00	FY_01	FY_02	FY_03	FY_04	FY_05	FY_06
6	1,213,163	1,350,736	1,464,358	1,788,300	1,632,519	2,022,845	2,095,808	1,764,336	1,670,597	1,256,474
7	1,185,902	1,408,672	1,074,767	1,045,417	1,007,355	791,244	686,961	571,811	508,275	124,323
8	1,450,542	2,171,877	2,581,374	3,591,689	4,860,642	5,528,144	5,019,216	4,504,226	3,205,779	1,376,208
9	254,059	503,470	419,738	355,487	556,105	596,964	448,976	508,236	372,951	221,811
10	1,850,289	2,530,209	3,351,308	2,383,228	3,097,630	3,162,858	2,560,337	1,620,646	1,140,279	1,134,561
11	40,029	19,650	12,084	124,115	95,620	109,436	28,630	17,201	21,880	58,800
12	1,033,449	1,613,494	712,591	629,645	426,828	380,796	211,268	286,882	168,575	307,497
13	28,725	75,020	79,400	6,080	7,290	1,000	1,160	620	3,000	33,603
14	69,785	12,730	25,730	28,550	11,240	9,920	6,100	600	3,180	47,332
15	76,375	30,660	18,430	12,480	23,406	17,470	7,950	73,210	23,800	145,979
20	60,460	10,100	33,293	19,715	1,100	3,670	9,980	3,340	23,257	169,706
25	12,806	12,300	0	0	1,200	0	0	900	173,885	318,730
30	3,400	1,400	0	0	0	0	4,500	9,230	1,157,726	3,674,990
Total	7,278,984	9,740,318	9,773,073	9,984,706	11,720,935	12,624,347	11,080,886	9,361,238	8,473,184	8,870,014

Figure 6 Percentage of hooks deployed each financial year within each of the hook-per-float categories used in the HBS model described in the text.



in some instances the profile of the most similar HPF configuration was used as a proxy as shown. A listing of the number of hooks deployed each year in the ETBF within each of the HPF categories used in the HBS model is shown in Table 6 while the percent of hooks each year within each HPF category is shown in Figure 6. For most years, the most common HPF categories used were 8, 10 and 12, with more than a third of all hooks deployed using an 8 HPF configuration during six of the ten years shown. However, there have been significant shifts in the HPF profile over time. Between 1997 and 2004 the percent of hooks deployed on configurations with less than 10 HPF increased from 56% to 78% while the percentage with 10-20 HPF configurations decreased from 43% to 22%. Less than one-percent of hooks during these years were deployed on configurations with more than 20 HPF. During the last two years the percentage of hooks deployed on configurations with more than 20 HPF has increased to 45%, with 21% deployed on 10-20 HPF and 33% on configurations with less than 10 HPF.

ii) Total catch for each year, C_y

We use the catch information (number of bigeye caught and discarded) recorded in the AFMA logbook data for each longline set. The catch is summed across all sets to provide an estimate of the total catch in each year.

iii) The proportion of hooks in each HPF category within each depth-stratum, $h_{ik.}$.

The profiles described in section 3 were used.

iii) The proportion of bigeye tuna within each depth-stratum, p_k.

We used the time-series of depth and temperature data collected by 15 archival tags retrieved from a total of 161 tags deployed on bigeye tuna in the Coral Sea between October 1999 and October 2001. Time at liberty for these tags varied between 16 and 1441 days. A full description of the tagging operations and the data collected is provided in Gunn et al (2005). The percent time-at-liberty versus depth profiles collected from these 15 tags are shown in Figure 7. Each profile displays the generally bi-modal distribution associated with the vertical diurnal movement of this species through the water column and observed for bigeye from other tagging experiments (Schaefer and Fuller 2002, Musyl et al. 2003). Unlike other applications where the temperature preference profile for the species of interest are combined with the spatial distribution of temperature-at-depth provided by Global Circulation Models to provide a species-depth profile within each spatial-temporal stratum in the model, here we just use the mean time-at-liberty versus depth profile over all tags to provide a time and space invariant estimate of the fish-depth profile, p_k, over the entire ETBF.

Two other variants were also fitted to the above model.

2) We assume a seasonal (i.e. quarter of the year) variation in the proportion of bigeye tuna with depth. Again, the tag data was used to determine the mean percentage of time at liberty versus depth within each season (1=Jan-Mar, 2=Apr-Jun, 3=Jul-Sep, 4=Oct-Dec). These profiles are shown if Figure 8. The effective effort was calculated for each quarter of the year, then summed across all four quarters to give the total effective effort for the year. In this instance, equation (4.2) becomes:

Figure 7. Percent time-at-liberty versus depth profiles collected from archival tags attached to 15 bigeye tuna tagged in the Coral Sea. The mean profile across all tags is also shown.

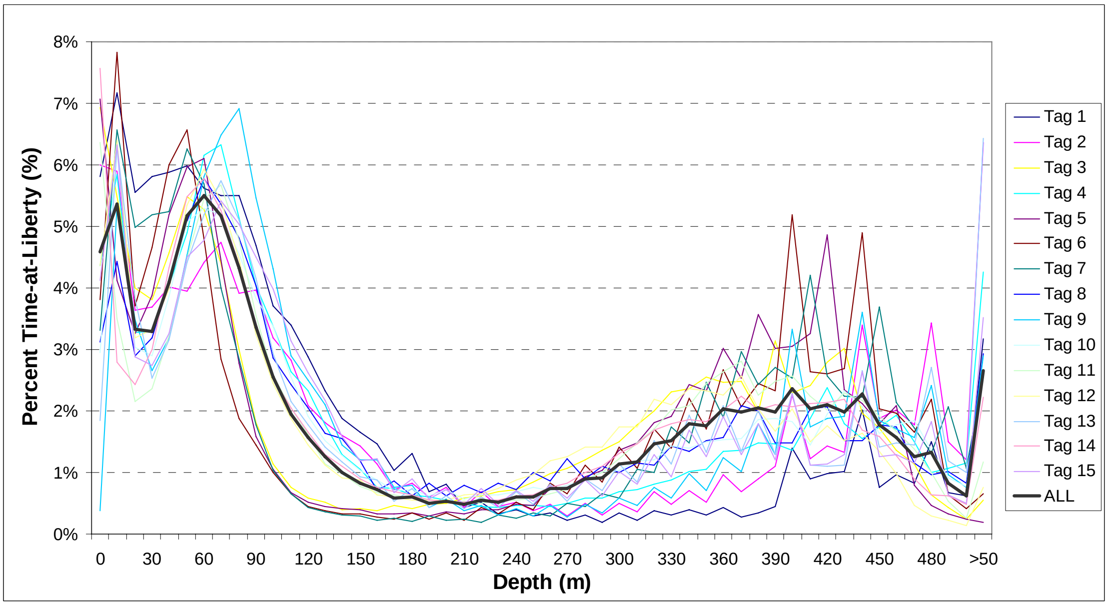


Figure 8. The mean percent time-at-liberty versus depth profiles collected from archival tags attached to 15 bigeye tuna tagged in the Coral Sea stratified by (a) season (quarter of the year) and (b) day and night.

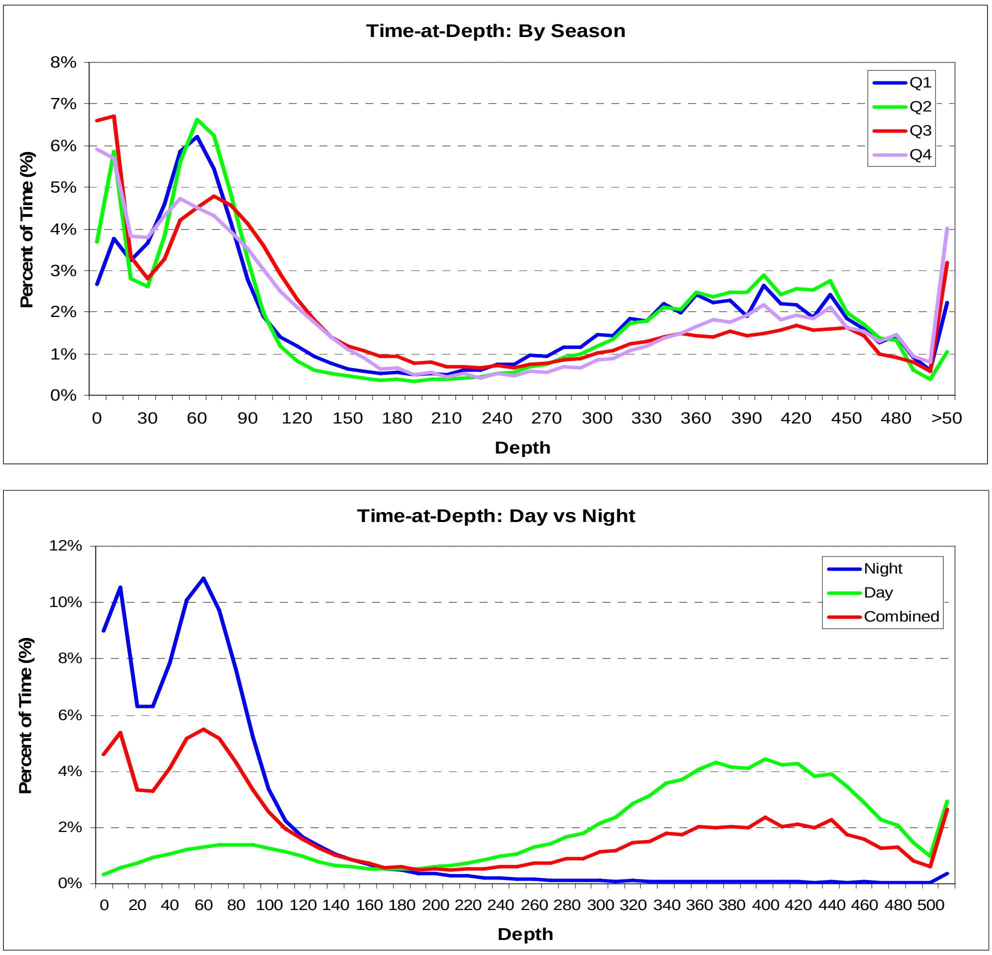
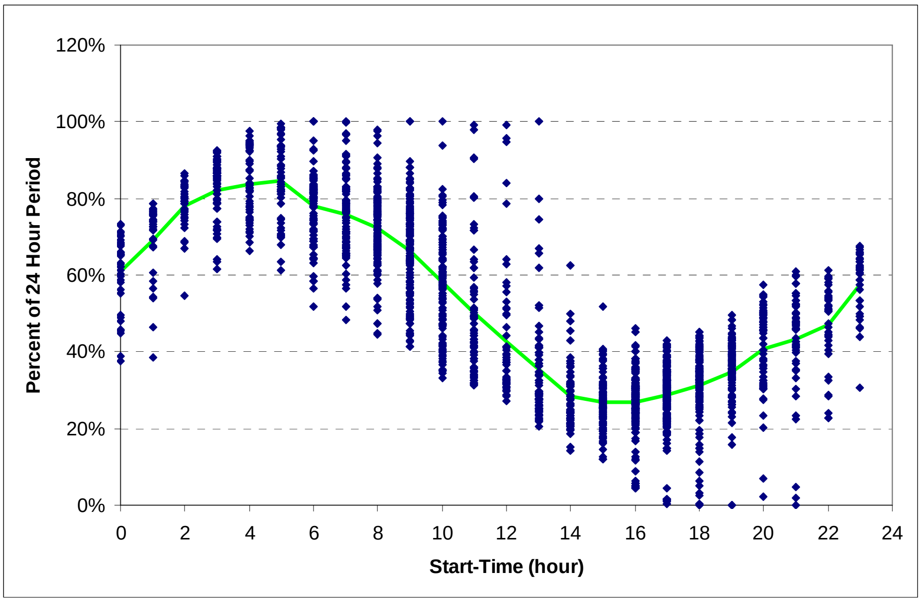


Figure 9. Proportion of each 24 hour period that the total soak of each observed set occurs during daylight hours, defined as between 6am and 6pm.



$$I_y = \frac{C_y}{\sum_{q=1}^{4}\sum_{i=1}^{N_c}\left(E_{iqy}\sum_{k=1}^{N_d} h_{ik}\, p_{qk}\right)} \qquad (4.3)$$

where: E_{iqy} is the total number of hooks deployed with HPF configuration i in quarter q in year y,

p_{qk} is the proportion of bigeye tuna in quarter q in depth stratum k (and were assumed to constant across all years).

As before we assume h_{ik}, the proportion of all hooks with HPF configuration i in depth stratum k, is constant across all quarters and years.

3) We assume a diurnal variation in the proportion of bigeye tuna with depth. Each longline set was classified into one of the following three set types - day, night or combined. However, as it was not possible to calculate for each set the proportion of the total soak that occurred during day-light hours, this classification was based on the hour of the day that the set commenced. Using the observer data collected from 2003 sets, the proportion of each 24 hour period that the total soak of each observed set occurred during daylight hours, defined as between 6am and 6pm, is shown in Figure 9. Using the mean proportion for each hour, P, and again defining a day-set as that where P>0.66 and a night set where P<0.33, then each set-type was defined as follows:

Day-set:	Set commences between 1am and 10am
Night –set	Set commences between 1pm and 8pm
Combined-set:	Set commences between 10am-1pm or 8pm-1am

The tag data was then used to determine the mean percentage of time at liberty versus depth within each day/night/combined period. The profiles for each period are shown in Figure 8b. The effective effort was calculated for each diurnal period, then summed across these periods to give the total effective effort for the year. In this instance, equation (4.2) becomes:

$$I_y = \frac{C_y}{\sum_{t=1}^{3}\sum_{i=1}^{N_c}\left(E_{ity}\sum_{k=1}^{N_d} h_{ik}\, p_{tk} \right)} \tag{4.4}$$

where: E_{ity} is the total number of hooks deployed with HPF configuration i in diurnal period t in year y,
p_{tk} is the proportion of bigeye tuna during diurnal period t in depth stratum k (and were assumed to constant across all years).

As before we assume h_{ik}, the proportion of all hooks with HPF configuration i in depth stratum k, is constant across all periods and years.

4.3 Results

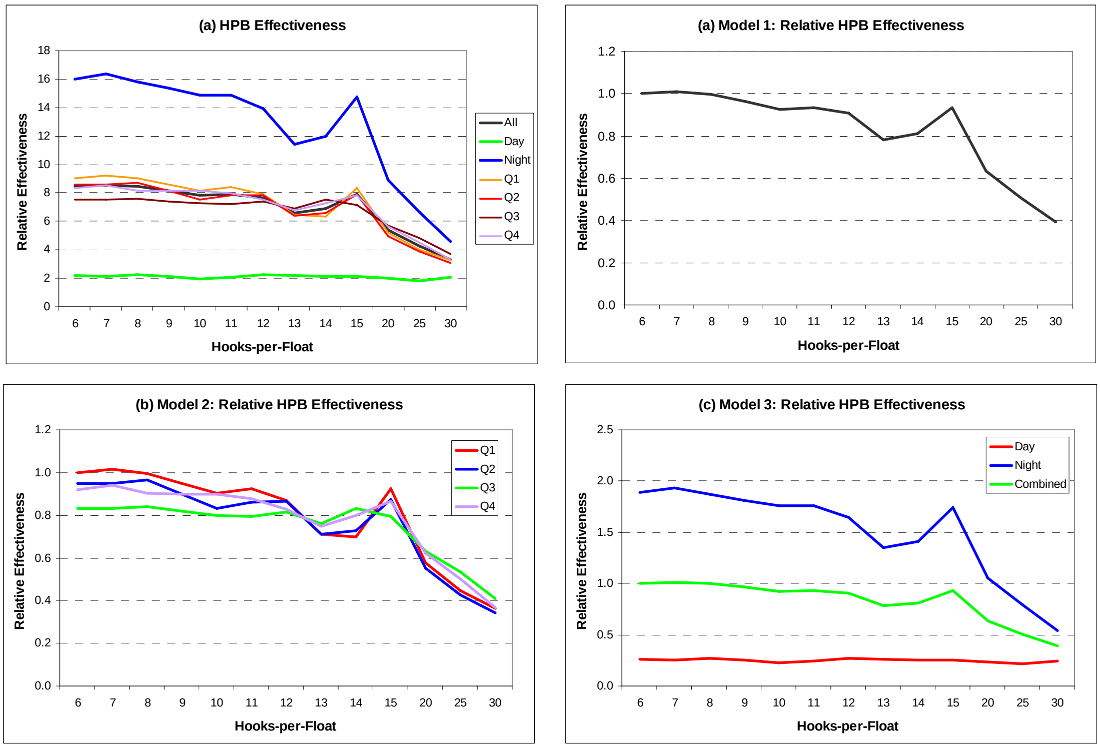
From equation (4.2) the effective effort can be written in the form:

$$EE_y = \sum_{i=1}^{N_c}\left(E_{iy}\sum_{k=1}^{N_d} h_{ik}\, p_k \right) = \sum_{i=1}^{N_c}\left(E_{iy} R_i \right) \tag{4.5}$$

where $R_i = \sum_{k=1}^{N_d} h_{ik}\, p_k$ (the cross product of the depth-profile of the hooks within each HPF configuration with the depth-profile of the fish) provides a measure of the effectiveness of the hooks in each HPF configuration in fishing for the target species. The values of R_i for each HPF configuration included in the models and for each of the three models fitted to the data are shown in Figure 10. In Figure 10a the raw values of R_i are displayed whilst in Figures 10b-d relative values are displayed for each of the three models. For model 1 the values of R_i have been made relative to the 6 HPF configuration, for Model 2 relative to the 6 HPF configuration deployed during quarter 1 (Jan-Mar), and in Model 3 relative to the 6 HPF configuration deployed during the combined period. (Note, in calculating the indices given by equations 4.2 - 4.4 it was found useful to adopt similar relative measures when calculating each R_i value as this helps to preserve the effort scale.)

These results indicate that there is a relative decrease in the effectiveness of hooks in targeting bigeye tuna as hooks are deployed in configurations with increasing HPF. For Model 1, hooks in a 13 HPF configuration are found to be only 80% as effective as hooks deployed in a 6 HPF configuration, while hooks in a 30 HPF configuration are found to be only 40% as effective. A similar pattern is also found for each of the four seasonal results. The most striking results are seen in those for Model 3, where the model took into account diurnal variation in the depths of the targeted fish. Hooks deployed in a 6 HPF configuration during the night are found to be more than 7 times as effective as hooks deployed in a similar configuration during the day. This result is explained by reference to Figures 2 and 8b where it is seen that there is great overlap in the depths of the hooks and bigeye during the night but relatively little overlap during the day. Consequently, hooks deployed in a 6 HPF configuration have a much greater effectiveness at targeting bigeye at night than during the day. The difference in relative effectiveness between deploying hooks during the night versus the day decreases as the number of HPF increases due to the fact that overlap of these hooks with the depth distribution of bigeye during the day decreases.

Figure 10. Relative effectiveness of each HPF configuration with (a) no temporal stratification and relative to a 6 HPF configuration, (b) a seasonal stratification and relative to a 6 HPF configuration deployed during season 1 (Jan-Mar) and (c) a day-night stratification and relative to a 6 HPF configuration deployed during the day.



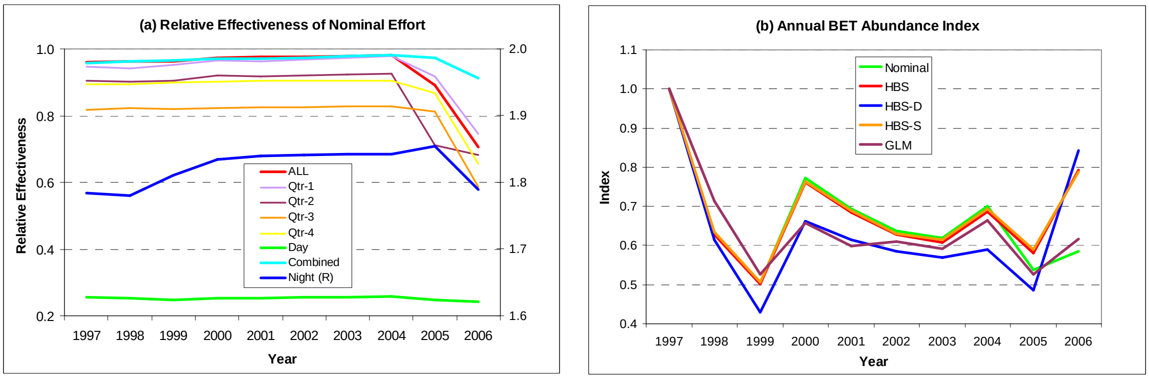
The effective effort calculated in equation (4.5) can be expressed in the following form:

$$EE_y = e_y E_y$$

where e_y is the relative effectiveness of the nominal effort E_y for the entire year. The values of e_y for each temporal stratification used in of the three models are shown in Figure 11a. As noted previously, effectiveness is relative to hooks deployed in a 6 HPF configuration and during one of the temporal strata used in the model (season 1 and combined set-types for models 2 and 3 respectively). All results, except that for the Night stratification, display a fairly constant effectiveness between 1997 and 2004, after which the effectiveness decreases significantly. This decrease coincides with the large increase in deploying 25 and 30 HPFs. The results for the four seasons indicate that effect is most effective during the first quarter (around 90% until 2004 then decreasing to around 75%) and least effective during the third quarter (around 83% until 2004 then decreasing to around 60%). The Night result again indicates that the effectiveness of hooks deployed during the night is around 7 times that of hooks deployed during the day.

Finally, the annual index calculated for each of the three models is shown in Figure 11b. These indices are compared with both the nominal CPUE for each year and an index based on a GLM where the effort has been standardised for a range of gear (HPF, bait, start-time of set, light-sticks used) and environmental (moon-phase, sea-surface temperature and southern-oscillation index) effects (Campbell 2008). Despite some differences in the size of the annual change, all indices display a similar pattern

Figure 11 (a) Relative effectiveness of nominal effort at targeting bigeye tuna (NB, values for Night effectiveness corresponds to right-hand axis), and (b) annual indices of bigeye abundance based on various CPUE models.



over the ten year time-series. However, there are some significant differences in the size of the change between years, with the model accounting for diurnal differences in effort effectiveness displaying the greatest changes between years and the greatest differences with the other indices. Of particular note is the large increase in the diurnal-model index in 2006. As noted, previously there was a large increase in the use of longline configurations with 30 HPF (up from 3.6% in 2005 to 40.4% in 2006, c.f. Figure 6) which resulted in a large decrease in the overall effectiveness of the hooks in targeting bigeye (c.f. Figure 11a).

4.4 An Alternative Temperature-based Model

The above modelling approach is premised on the belief that the distribution of the target fish in the water column is determined by depth alone, and that if one knows this depth distribution then one can match this with the depth distribution of the hooks to determine the effectiveness of these hooks. An alternative approach is to assume that the distribution of the target fish in the water column is determined by water temperature. Then if one knows the temperature distribution of the fish then one can match this with the distribution of temperature fished by the hooks to determine the effectiveness of these hooks.

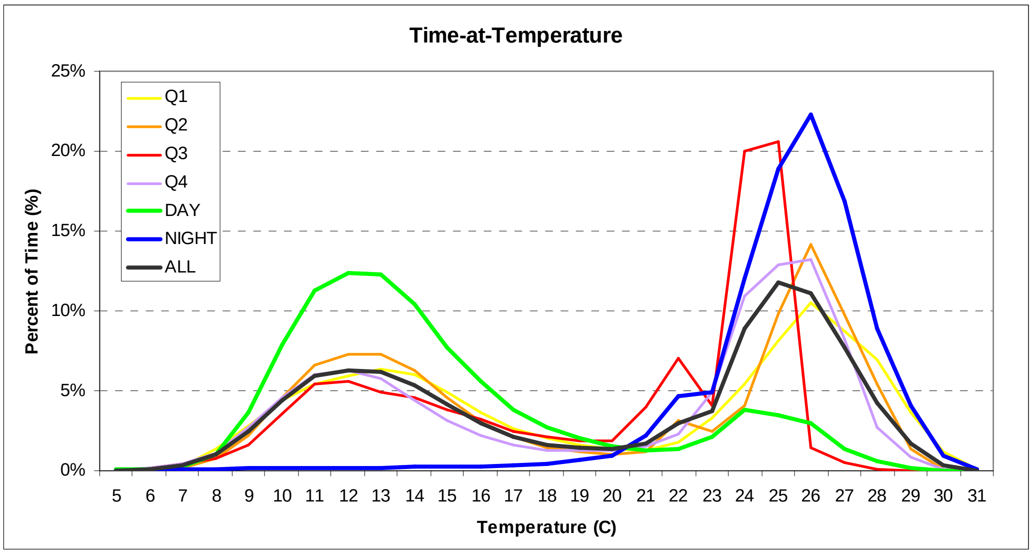
Using this alternative approach, the model equations are obtained by simply replacing the depth stratification of the water column by stratification based on temperature. Hence, equation (5) can be rewritten as follows:

$$I_y = \frac{C_y}{\sum_{i=1}^{N_c}\left(E_{iy}\sum_{k=1}^{N_T} h_{ik}\,p_k\right)} \tag{4.6}$$

where:

C_y is the total number of bigeye tuna caught in year y,
E_{iy} is the number of hooks deployed within HPF category i in year y,
h_{ik} is the proportion of hooks within HPF category i in temperature stratum k,
p_k is the proportion of bigeye tuna in temperature stratum k,
N_T is the number of temperature stratum in the model,
N_C is the number of HPF categories used in the model.

Figure 12. The mean percent time-at-liberty versus temperature profile collected from archival tags attached to 15 bigeye tuna tagged in the Coral Sea. The mean profiles stratified by (a) season (quarter of the year) and (b) day and night are also shown.



Compared to the previous depth-based model the only new information required to apply this model is the information on h_{ik}, the proportion of hooks within HPF category i in temperature stratum k, and p_k, the proportion of bigeye tuna in temperature stratum k. The former were calculated from the TDR data (in a similar manner to the depth profiles shown in Figure 2) whilst the latter information was again based on the data collected from the 15 archival tags retrieved from the bigeye tuna tagged in the Coral Sea. The mean percent time-at-liberty versus temperature profile collected these tags, together with the mean profiles stratified by season (quarter of the year) and day-versus night are shown in Figure 12.

The results from applying the above model are shown in Figures 13 and 14. The raw and relative values of the HPF effectiveness term, $R_i = \sum_{k=1}^{N_T} h_{ik} p_k$ (shown in Figure 13) indicate a pattern of relative HPF effectiveness quite different to that seen for the depth-based model. Unlike the previous declines in effectiveness with increasing HPF, this model indicates that while there can be large differences in effectiveness between HPF categories there is no overall trend as HPF increases. Nevertheless, like the previous depth-based models, those temperature-based models with additional temporal stratification of the data also show significant differences in the effectiveness between temporal strata. For example, most HPF categories are 2-3 times more effect during the third quarter (Jul-Sep) than during the first and second quarters, while the average difference in effectiveness between the fourth quarter and the first quarter is around 50 percent. The deployment of hooks at night is also, on average, 2.5 times as effective as day deployments.

The overall effectiveness of all hooks deployed each year, relative to the nominal effort, is shown in Figure 14a. Like the previous depth-based models, the effectiveness for each season is relatively constant across years before decreasing significantly in the last two years (again due to the increase in 25 and 30 HPF configurations). On the

Figure 13. Relative effectiveness of each HPF configuration based on the temperature-based model with (a) no temporal stratification and relative to a 6 HPF configuration, (b) a seasonal stratification and relative to a 6 HPF configuration deployed during season 1 (Jan-Mar) and (c) a diurnal stratification and relative to a 6 HPF configuration deployed during the combined period.

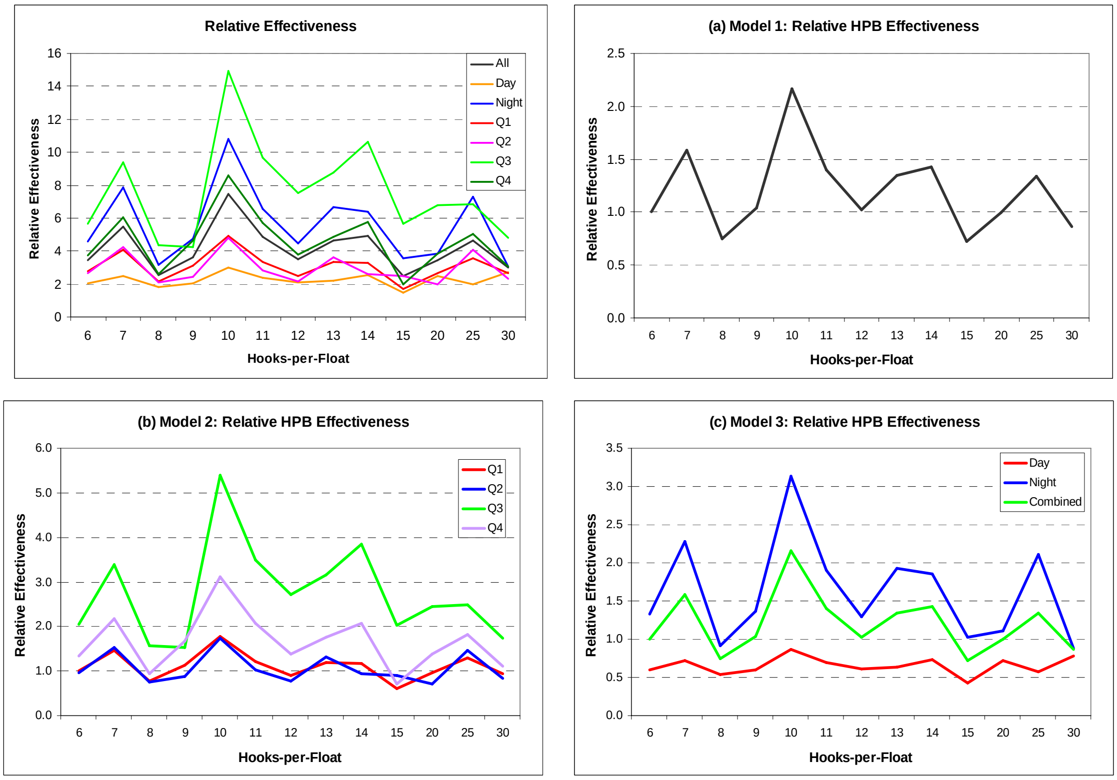
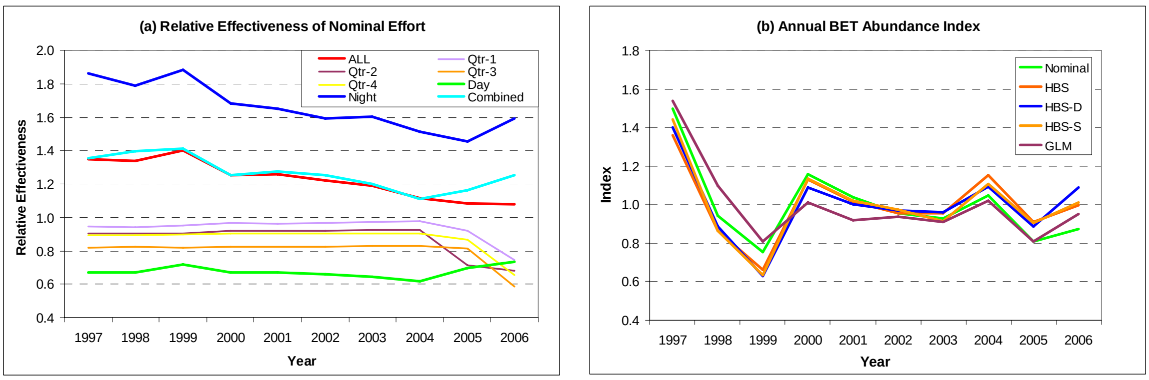


Figure 14. Results for the temperature-based model: (a) Relative effectiveness of nominal effort at targeting bigeye tuna, and (b) annual indices of bigeye abundance based on various CPUE models.



other hand, there is a decrease in effectiveness over time for hooks deployed during the night resulting in a similar, but smaller decrease, in the effectiveness of all hooks.

Finally, the annual indices of bigeye tuna abundance, shown in Figure 14b, display less variability compared to those based on the depth-based models with the overall trend since closer to the GLM-based index.

4.5 Application of detHBS and statHBS

As noted previously, the application of the HBS method to the ETBF data made a number of simplifying assumptions. In particular, the habitat preference profile was assumed to be a function of depth or temperature alone and the same profile was assumed to apply across all areas of the fishery. In the original HBS method, the habitat-at-depth profile was assumed to be a function of temperature and dissolved-oxygen preferences, and the distribution of these two physical elements across each spatial area, mapped using an Ocean Global Circulation Model (OGCM) was used to determine the depth-profile within each area. In the application above we have circumvented this process by simply using the mean time-at-depth profile obtained from the archival tags data. One could overcome the second simplifying assumption mentioned above by simply stratifying the archival data by area and then determining a unique time-at-depth profile within each area.

The habitat-based standardisation methods outlined above are often called "deterministic." This is because it assumed that all the components of the model, including the habitat preference, are known and once all the data elements have been obtained, the data is simply fitted to the model equations in a deterministic and non-statistical manner. However, more recently this approach has been modified to allow for the recognition that there is uncertainty in the habitat preference estimates. In particular, it is assumed that the temperature preference profile is uncertain and this profile is estimated from the model using the temperature preference data provided by the tag observations as a given prior (Maunder et al 2005). This approach has since become known as the statHBS method and has been applied to both bigeye and yellowfin tuna within the WCPO (Bigelow et al 2003, Langley et al, 2005).

Both the detHBS and statHBS method was applied to the bigeye data for the ETBF and the results compared with the results based on the two alternative tag-only based preference models applied in the previous sections (identified, as before, as the HBS-D and HBS-T models). Some missing data in the OGCM (mainly in the northern part of the ETBF) resulted in around 6 percent of the data records not been used. A full description of the methods and OGCM data used is provided in Bigelow (2006). Each method was applied separately to the three diurnal periods identified previously - Day, Night and a Combined day/night period. A comparison of the resulting standardised annual CPUE index for bigeye is shown in Figure 15a whilst a comparison of the estimated temperature-preference profile from the statHBS method with the tag-data based prior is shown in Figure 15b. In order to provide a better quantitative measure of similarity between different indices, the absolute percentage difference between any two indices *i* and *j* in year *k* was calculated and then the mean calculated across all years, *N*, i.e.

$$S_{ij} = \frac{100}{N} \sum_{k=1}^{N} \frac{abs\left(I_{ik} - I_{jk}\right)}{I_{jk}}$$

The values of S_{ij} for each diurnal period and each standardisation method are listed in Table 7.

Figure 15 (a) Comparison of annual bigeye abundance indices based on the statHBS, detHBS and the two tagged-only based HBS methods applied to the data for each of the three identified diurnal periods (note, all indices are scaled such that the mean across the time-series is one) and (b) comparison of the prior (tag-data) temperature preference profile with that estimated from the statHBS model.

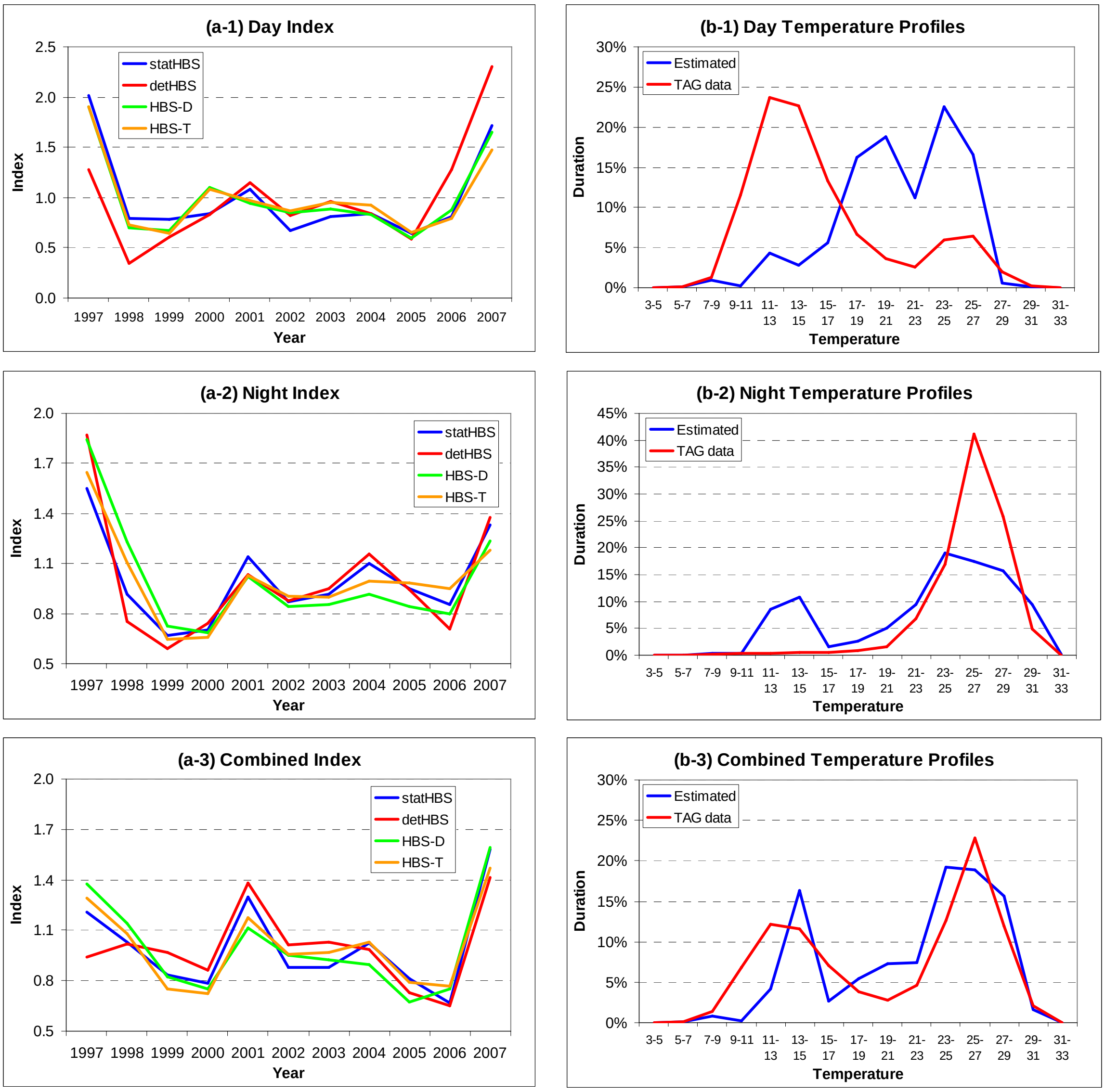


Table 7. Measure of similarity between the annual standardised CPUE-based indices for each period and standardisation method.

Period	DAY				NIGHT				COMBINED			
Method	statHBS	detHBS	HBS-D	HBS-T	statHBS	detHBS	HBS-D	HBS-T	statHBS	detHBS	HBS-D	HBS-T
statHBS		24%	12%	13%		9%	11%	8%		10%	9%	8%
detHBS	30%		26%	28%	9%		15%	14%	10%		15%	13%
HBS-D	11%	22%		6%	11%	13%		9%	9%	14%		7%
HBS-T	12%	25%	6%		8%	13%	8%		8%	13%	7%	
Mean	18%	24%	14%	16%	9%	11%	12%	10%	9%	13%	10%	9%

For both the Day and Combined periods the HBS-D and HBS-T indices are seen to be the most similar while for the Night period the statHBS and HBS-T are most similar. On the other hand, for all periods the indices based on the detHBS method are generally the most dissimilar from the three other indices (though this different is small for the Night period). This result is perhaps somewhat surprising, as the detHBS and the two tag-based indices both make "deterministic" use of the tag data while the statHBS method allows more freedom for the temperature profile to be determined by the catch and effort data. In this regard, this result raises the issue of what elements of the data are perhaps to most important and accurately measured from a habitat perspective. While the depth and temperature data retrieved from the archival tags are deemed to be relatively accurate, on the other hand the accuracy of the distributions of temperature and dissolved-oxygen profiles taken from any OGCM are likely to only approximate the true distributions of these variables. At worst is could be inaccurate and unreliable. How approximate and how reliable these data are remains uncertain and whether the use of this OGCM data is biasing the standardised indices also remains uncertain. The model for which the accuracy of the OGCM data is most important is the detHBS model and it is therefore of interest that the results of this model are the most different in comparison to those from the other two models.

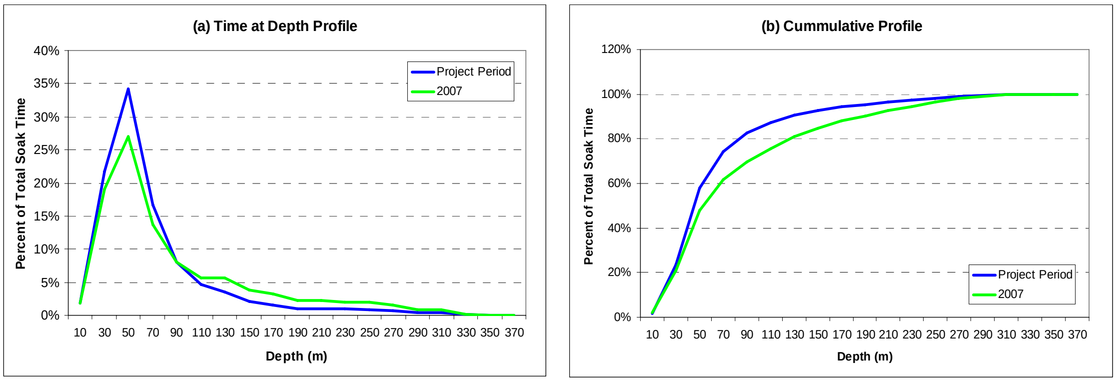
Finally, the estimated temperature profiles from the statHBS model show several major differences when compared to the tag-based profiles (c.f. Figure 15b). This is most clearly seen in the profiles for the Day period. The tag-based profiles indicate that during this period bigeye spend the majority of their time in temperatures between 10-15C with a smaller mode between 24-27C. However, the statHBS model estimates that bigeye spend nearly all their time during the day at temperatures above 17C. Differences are also seen in the Night-period profiles, thought the two profiles for the Combined period are the relatively similar. Again, the reliability of the data provided by the OCGMs is important in the estimation of these temperature profiles, and biases in these data would propagate through to the estimated profiles. Whether or not this is the reason behind the differences noted remains uncertain. However, despite these concerns, it is interesting to note that the HBS-T and statHBS indices are most similar for the Night and Combined Periods.

5. Discussion

5.1 Depths Fished by Longline Hooks

The TDR data collected during this project has shown that hooks deployed in the ETBF longline fishery fish a range of depths down to around 400m, with the deepest recorded depth being 395 m. The depth profiles fished by sets deploying less than 10 HPF were found to be very similar, though the depth-profiles associated with those sets deploying more than 15 HPF were considerably deeper. As most sets identified by observers as targeting yellowfin, bigeye or swordfish generally deploy less than 10 HPF, the depths fished by hooks targeting each of these species were found to be similar. This result indicates that this variable has little discriminating power in distinguishing different fishing practices and targeted depths associated with these three species. On the other hand, a near linear relationship was found in the mean depth fished by all hooks within a HPF configuration and the number of HPF. This

Figure 16 Aggregate total soak-time versus (a) depth and (b) temperature for all sets in the ETBF projected during the period of the project.

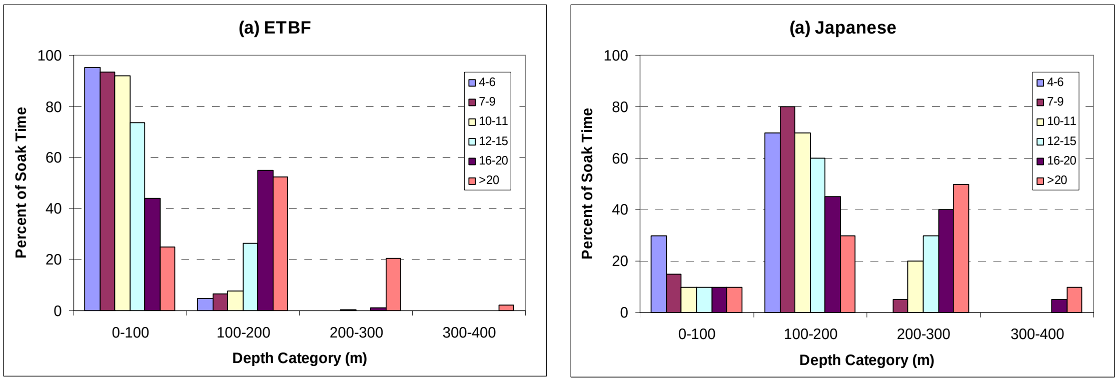


result supports the assumptions often used in the CPUE standardisation models for longline fishing that the number of HPF is a proxy for fishing depth.

Combining the observed depth-profiles associated with each HPF configuration with the profile of sets deploying each HPF configuration provides a profile of depths for all hooks deployed in the ETBF. This profile is shown in Figure 16 for all sets deployed in the ETBF during the period that TDRs were deployed (August 2004 to May 2007) and for all sets deployed during 2007. These profiles indicate that the most common depths fished by hooks are relatively shallow, with 34 percent of all hooks deployed during the project period being between 40-60 meters. Around 75 percent of these hooks fished depths below 80 meters while only 10 percent of hooks fished depths greater than 140 meters. Due to the greater deployment of "deep" sets deploying 20 or more HPF the depth profile for all sets during 2007 is deeper, with around 20 percent of hooks fishing below 140 meters and 10 percent fishing below 200 meters.

It is informative to compare the estimated depth profiles of hooks observed in the ETBF with those estimated for Japanese longliners. The latter were estimated by Hampton et al (1998) based on a number of studies undertaken by Japanese scientists and are shown in Figure 16 for a range of HPF categories. The corresponding depth-profiles observed in the ETBF (based on combining the depth profiles shown in Figure 2) are also shown. The two sets of profiles are seen to be very different with Japanese hooks estimated to fish considerably greater depths than hooks deployed in the ETF. For example, hooks deployed within the ETBF using configurations of less than 15 HPF generally spend more than 70 percent of their time at depths less than 100m, while corresponding hooks deployed by Japanese longliners are estimated to spend more than 60 percent of their time at depths between 100-200 meters. The same pattern is also seen for sets deploying a higher number of HPF. The reasons for these significant differences in depths remain uncertain, but are most likely due to shorter branchlines and floatlines used in the ETBF and the smaller sag angle. This result also indicates that the deployment of the longline can vary significantly between fishing fleets as can the depths fished by the deployed hooks. This, in turn, will limit the application of the habitat-based method of standardising catch rates to those fleets for which the depth-profiles of the hooks has been ascertained.

Figure 16. Estimated depth profiles for respective HPF categories for (a) ETBF longliners and (b) Japanese longliners.



5.2 Capture Depths of Species

The estimates of catch-depth profiles indicated that although there were significant differences in the catch rates of the different species between gears deploying different HPF configurations, the associated depth-profiles were usually very similar. Indeed, the profiles for each of these five species for HPF configurations with less than 10 hooks were practically identical indicating that for these sets the availability of each species with depth was also relatively the same over the range of depths fished by these gears. The profiles for gears deploying between 10 and 25 HPF were also very similar indicting a similar result.

The above results are quite surprising as it is usually assumed that each species has a different profile of availability with depth with the consequence that the catch rates obtained from different parts of the longline gear (eg. deeper versus shallower hooks) will vary dependent on how closely the depth-profile of the hooks overlaps this availability profile. For example, it is often believed that shallower hooks achieve higher catch rates of yellowfin tuna and deeper hooks achieve higher catch rates of bigeye tuna. However, no evidence was observed for such systematic differences in catch rates across different parts of the same longline gears fishing different depths. Only for sets with 30 HPF was it observed that the catch of bigeye tuna generally occurred on deeper hooks than yellowfin tuna.

Despite these similarities within HPF configurations, there were nevertheless large and significant differences observed in the mean catch rates between sets deploying different HPF configurations. As a consequence, it was possible to discern major differences in the average availability-by-depth across the five main target species. For yellowfin tuna availability was estimated to be highest in the top 40 meters (as generally expected) and to then decline with depth, though availability was estimated to remain quite high down to around 200 meters. This increased understanding of the availability of yellowfin down to these deeper depths has been one of the unforeseen benefits of the move to deeper longlining that accompanied the increased targeting of albacore tuna a few years ago. On the other hand, availability for albacore was estimated to be relatively low in the upper parts of the water column and to be highest between 150-200 meters, though remaining high at deeper depths down to 310m. Bigeye tuna availability was found to be more evenly distributed with depth, though with a preference for higher availability at deeper depths. Availability for both swordfish and striped marlin was found to be low at depths below 150m and again highest in the top 40 m. It will be interesting to compare these results with the time-at-depth data being collected for species such as swordfish and yellowfin tuna from the recent and ongoing deployment of archival tags within the ETBF.

5.3 Habitat-Based Standardisation Models

The HBS method of standardising CPUE provides an alternative to the usual approaches based on the application of a statistical-based GLM or GAM. In particular, it provides an opportunity to use our increasing knowledge of the distribution of the target species and the fishing gears more directly. Information on the depth distributions of the target species is being obtained from the increasing use of archival tags whilst information on the depth-distributions of the fishing gears can be obtained from the deployment of depth monitors such as the TDRs utilised in this project. However, while the theory behind the HBS method remains valid the utility of the method remains somewhat constrained by the applicability and accuracy of the data required.

In past applications of the HBS method to yellowfin and bigeye tuna in the WCPO three sets of data have been used. The first consists of the estimated depth-distributions of Japanese longline hooks. However, as there has been no systematic survey of the depths attained by hooks deployed by Japanese longliners, the accuracy of these latter estimates remains unknown. Furthermore, as highlighted in the previous section one cannot assume similar depth distributions for hooks deployed by different fleets.

The second set of data used in the HBS models consists of the temperature and depth preferences of these species obtained from the deployment of archival tags in several regions of the WCPO. However, as the regions of the WCPO included in the assessment models are large, it has been assumed that the habitat preferences for each species are uniform across these regions. Without further information from the wider deployment of archival tags the accuracy of this assumption also remains unknown, but given that there are gradients in water temperatures (as well as changes in the depth of the thermocline) across the Pacific it is possible that these preferences may vary within a single region. Indeed, differences observed in the time-at-temperature histograms for bigeye tuna tagged within the Coral Sea and in the waters off PNG indicates the possibility of such differences between two relatively close areas (Bigelow et al 2004). While the number of tags deployed in each region of the WCPO varies, with very few being deployed in some regions, ongoing deployment of such tags should improve both the general utility of the observations and the coverage within regions.

Together with the assumption concerning the extrapolation of the archival data over wide spatial regions is the related issue of the lack of any temporal stratification of the habitat preferences in the application of the HBS model in the WCPO. For example, the application of the method has been limited due to the fact that the time of deployment of the Japanese sets has not been included in the available catch and effort data and as such it has not been possible to stratify the HBS model by time-of-day as undertaken for the ETBF analyses. It is well know that the habitat preferences for bigeye tuna vary significantly on a day-night basis and, as the results for the ETBF indicate, accounting for differences in set times can have a significant impact on the calculated annual abundance index .

Finally, the third set of data used in the HBS models consists of the temperature-at-depth data estimated from an Ocean General Circulation Model (OGCM) and which are used together with the time-at-temperature data obtained from the archival tags to estimate the depth distribution of the species of interest across the WCPO. However, as the accuracy of these OGCMs is yet to be tested it remains an open question as to how accurately these depth distributions are being estimated. Furthermore, given that the temperature preferences for some species such as bigeye tuna vary significantly on a diurnal basis, it remains unclear as to how suitable is the use of a single temperature profile based on the combination of day and night preferences.

The analyses undertaken for the ETBF attempted to overcome a number of these problems. First, there was a large scale survey undertaken of the depths fished by the hooks deployed in the ETBF so that the mean depth-profile for each HPF configuration was ascertained to a reasonable degree of accuracy. Second, the archival tag data used to determine the temperature and depth-profile of bigeye tuna in the ETBF was based on data collected from tags deployed within the ETBF. This overcomes the problem of having to extrapolate this data over too great a region. Third, a seasonal and diurnal component was added to the HBS model to allow for difference in the habitat preferences over these temporal periods. Addition of the diurnal component was made possible by use of set-by-set data with known set times and is the first time that such an analysis has been undertaken with an HBS model. Finally, in order to test and possibly circumvent the issue of the using possibly inaccurate OGCM estimates of temperature-at-depth distributions, a number of different approaches were adopted and the results compared. In the initial two approaches was assumed that there was a single depth or temperature profile for all bigeye in the ETBF similar to those obtained from the tag-based observations. This negates having to use an OGCM. Alternatively, the traditional deterministic and statistical approaches making use of the data from an OGCM were utilised.

The results based on the models utilizing the above improvements in data and model indicated that addition of the diurnal component to the model made a significant difference to the result. This is not unexpected, as it is well known that the depth and temperature preferences for bigeye tuna are significantly different between the day and night and there have been shifts over time in the proportion of sets in the ETBF deployed during the day and night. Obviously where such shifts like this occur, it is important to include these in any standardising model.

Comparison of the resulting indices across the four different approaches to using the tag and OGCM data found that the deterministic HBS model was the most dissimilar to the other three indices, with the two tag-based and the statHBS indices being quite similar. In the detHBS model the OGCM and tag data are combined deterministically to obtain the depth-distributions of the fish across the fishery. On the other hand, in the statHBS model the tag-based temperature-at-depth distribution is only used as a prior and this temperature profile is allowed to be modified in order to obtain a better fit. However, this model still relies on the use of the OGCM data in a deterministic manner. It is interesting then to note that the results of the statHBS model are most similar to the results which only rely on the deterministic use of the tag-data. One can infer from this result that the statHBS model needs to modify the tag-based temperature-preference profile of the fish in order to overcome the biases inherent in the use of inaccurate OGCM data to obtain a similar result where the tag-based depth-preference profiles have been assumed to be correct and the OGCM data has not been used. The amount of tag-based observations on habitat preferences continues to increase and while the spatial coverage of this data can be improved, within a single fishery such as the ETBF this result indicates that it is perhaps preferable to assume that the tag data more accurately reflects the habitat preferences of the fish across the fishery than some other model with relies on the use of possibly inaccurate OGCM data.

Furthermore, the statHBS and detHBS models both assume the depth profiles of the fish are determined to a large degree by the temperature profiles of the water column. However, such models do not allow for significant shifts in depth-preferences of fish which are not related to temperature preferences. For example, it is well established that species such as bigeye tuna undergo large vertical shifts in depth preferences between the day and night despite the water temperature profiles remaining relatively constant. In these situations it is obvious that the fish are responding to other changes in the habitat apart from water temperature, such as diurnal shifts in the feeding layer. If this is the case, then a habitat model based on temperature profiles alone will not be able to accurately model these diurnal shifts. In this situation, the direct use of observations which provides information on changes in the depth-profiles of the fish, such as those obtained from tag-data, may be preferable to use of modelled data (such as OGCM) where the required information is missing.

To the extent that the spatial coverage of the tag-based observations currently remains limited, and if one believes that there are differences in the habitat profiles and habitat preferences across larger spatial region, then if one to continue using the HBS models there remains a need to obtain information on the spatial distribution of the habitat across these larger regions, such as is currently obtained from the OGCMs. However, unless the data from the OGCM can be verified to some extent, the uncertainties expressed above about the use of this data will remain. If this remains the situation then it would perhaps be more prudent to commence a coordinated program of deploying archival tags across the WCPO so that a systematic mapping of the habitat preferences of each primary target species can be obtained.

Finally, the HBS method was developed to provide an alternative means of standardising CPUE which made direct use of the data on the habitat preferences of fish being obtained from the deployment of archival tags over the past decade. However, whilst the HBS method provides a more direct method of matching habitat usage with the depth profiles of longline hooks, it currently does not encompass other factors which also influence the catchability of a longline hook such as bait type, use of lightsticks, etc. As such there still remains a role for the use of the more traditional statistical GLM in standardising catch rates. Comparisons of the results of both GLM and HBS based approaches for the ETBF display some differences which may be overcome by the development of a third approach which combines aspects of both methods. It is recommended that this remains the focus of ongoing research.

Acknowledgements

As usual, this project would not have been possible with the support and assistance of a range of people. In no particular order the authors would therefore like to thank the following:

- The AFMA Observer Program. In particular, Andrew Bayne, Steve Hall, Craig Bambling, Dave Penson, Nathan Bicknell, Matt Preston Martin Scott and Steve Auld.
- The skippers and crews of all vessels who participated in the trips where Temperature-Depth-Recorders and Hook-Timers were deployed.
- Matt Lansdell, CSIRO Marine and Atmospheric Research, Hobart, for coordinating the deployment of the gear monitors with AFMA observers.
- Matt Sherlock, CSIRO Marine and Atmospheric Research, Hobart, for technical assistance with use the Temperature-Depth-Recorders.
- Baldur Sigurgeirsson, at Star-Oddi, Iceland, for his assistance in dealing with warrantee issues in relation to Temperature-Depth-Recorders.
- Jason Hartog, Karen Evans and Scott Cooper, CSIRO Marine and Atmospheric Research, Hobart for supplying the water current data and assistance with the archival tag data.

Finally, thanks also go to the Australian Fisheries Management Authority and the Fisheries Research and Development Corporation for financial support.

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