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Running head: Use of acoustic tagging data for abundance indices

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Abstract

Juvenile southern bluefin tuna (SBT, *Thunnus maccoyii*), migrate down the coast of Western Australia reaching the southern coast at age-1. In these waters an acoustic survey for SBT schools was initiated to generate a fisheries-independent abundance index. A decline in this abundance index led to an acoustic tagging and monitoring project to determine if a change in migration route or timing could explain the decline. Five years of acoustic monitoring revealed interannual differences in key factors that could impact the abundance index. Acoustic tag data were used to demonstrate that (i) a high proportion of fish (~70%) may be too shallow for detection in the acoustic survey, and that interannual variation in (ii) inshore-offshore fraction (~30-70% each year) and (iii) residence time (12 – 37 days) will impact calculation of an index. These factors should be included in estimating an abundance index for SBT, together with a correction for (iv) the fraction of juvenile SBT that migrate to southern Western Australia. Collectively, these results illustrate how electronic tagging data can be used to improve understanding of abundance patterns necessary for sustainable management of this exploited species.

Introduction

Southern bluefin tuna (SBT, *Thunnus maccoyii*) are an economically important species internationally and in Australia, however, they are currently at historically low population levels (Caton 1991; CCSBT 2007; Hobday et al. in review). SBT spawn in the northeast Indian Ocean between October and February (Farley and Davis 1998). Juvenile SBT move down the west coast of Australia and occur as age-1 and 2-year old fish in southern Western Australia and until about age-5 occur further east in the shelf waters of the Great Australia Bight during the austral summer (Caton 1991; Cowling et al. 2003; Willis and Hobday 2007). SBT are a highly exploited species with international management by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) (Polacheck 2002; Hobday and Hartmann 2006; Hobday et al. in review). One of the continuing CCSBT research priorities has been to develop a fishery-independent recruitment index for SBT (e.g. CCSBT 2007), particularly for age-1 fish in southern Western Australia. Such an index is seen as crucial to detect potential recruitment failure years before similar signals might be detected in CPUE analyses based on high seas fisheries data.

In southern Western Australia, a ship-based acoustic survey was initiated in 1995 to estimate the relative abundance of 1-year old SBT (Itoh and Tsuji 2004, **Figure 1a**), with the goal of generating a fishery-independent recruitment index. The survey, conducted in January-February of each year, consisted of repeat transects within the survey area. Schools of SBT were identified on the vessel sonar and echo-sounder images by experts, and school biomass estimated (Itoh and Tsuji 2004). Beginning in about 2000, however, the abundance of juvenile SBT within the acoustic survey area declined dramatically, leading to very low abundance indices (**Figure 1b)**. It was suggested that either (i) changes in the migration behavior of juvenile SBT or (ii) a real decline in the number of juvenile fish was responsible for the apparent change in SBT abundance. Acoustic monitoring of SBT using tags and moored receivers was initiated in 2001/02 to examine the first possibility; a change in migration behavior in southern Western Australia had occurred.

Two alternative migration hypotheses were that juvenile SBT (i) were now moving inshore of the acoustic survey area, or (ii) were moving through the area before the survey had commenced. Examining the SBT migration timing and pathway was thus considered crucial to correctly interpret the abundance indices and assess population trends of this exploited species. Key needs were to determine how quickly juvenile SBT move east along the southern Western Australia coast during the austral summer, and how close to shore the movements occur, in particular, would they avoid detection in the acoustic survey (Hobday 2003).

Information on behavior and movement of 3, 4 and 5-year old SBT in southern Australia has been successfully obtained using internal archival tags (Gunn et al. 1995), however, these tags do not provide location information on a fine horizontal scale (< 60 nautical miles) (Welch and Eveson 1999; Musyl et al. 2001; Teo et al. 2004), and so were not suited to this problem. An alternative approach with finer resolution was required and funded through the Japan-Australia Recruitment Monitoring Program (RMP). This approach, using acoustic tags and moored acoustic receivers that detect tagged fish, had been developed and tested in both Western Australia (Hobday et al. 2001) and South Australia (Hobday 2002) and was appropriate for SBT movement studies at scales of 1-100 km (Heupel et al. 2006).

In this paper, we summarize the results from five years of acoustic monitoring experiments (2002-03 to 2006-07), and demonstrate how results obtained using this technology can be used to correct an abundance index for SBT. Before describing the experimental design of the acoustic experiment, we first describe how the results from acoustic tagging and monitoring can assist the refinement of an abundance index.

An abundance index for southern bluefin tuna

In the early years of the acoustic survey, while SBT abundance was high, it was implicitly assumed that all fish passed through the survey area, such that,

$$N_{fish} \approx E_{fish} \qquad (1)$$

where N_{fish}, the final abundance index, is proportional to E_{fish}, the estimated abundance based on the fish that were encountered during the survey (**Figure 1b**). While it was recognized that other factors could also impact on the encounter rate of schools, these factors were assumed to be constant over years. Multiple replicates of the survey each year (8-12 per year) also allowed confidence intervals to be calculated.

Early results from the acoustic monitoring experiment showed that the fraction of fish encountered within the survey area varied according to several factors with interannual variation, such that the estimate of the abundance index could be expressed as,

$$N_{fish} \approx E_{fish} \bullet D_{detection} \bullet F_{offshore} \bullet T_{survey}/T_{residence} \qquad (2)$$

where, $D_{detection}$ is the proportion of fish swimming at a depth such that they can be detected by the acoustic survey instruments, $F_{offshore}$ is the fraction of fish swimming through the survey area (compared with the fraction swimming inshore), and $T_{residence}$ is the time in days for the fish to pass through the survey region. The time to complete an acoustic transect is T_{survey}. If fish move through the survey area more slowly than the survey vessel (long residence time), then fish may be double counted on subsequent transects, or an assumption of relative stationarity may be valid, while if fish pass through the survey area more rapidly than the survey vessel completes transects (short residence time), then the abundance of SBT may be underestimated. This paper will illustrate how each of these factors was obtained from the acoustic monitoring of SBT, and thus demonstrate how tag data can be used to advance sustainable management. Movement pathways of individual fish are not presented here, it is the population level descriptions of movement that are the focus and required to correctly estimate an abundance index.

Methods

Information on the distribution and movement of juvenile SBT was gathered using acoustic receivers and acoustic tags. We first describe the data collection, and then the data analyses conducted to allow corrections to the abundance index.

Data collection

Listening stations consisted of a mooring anchor (125 kg section of railway track), wire cable, VEMCO VR2 receiver, timed electronic release, 50 meters of release rope in a PVC canister, and floats. VEMCO temperature-depth recorders (TDR) were attached to a subset of receivers at regularly spaced intervals to provide environmental data. When deployed, the receivers were at a depth of 20-25 meters, just below the sub-surface floats (**Figure 2)**. Receivers were deployed in cross-shelf lines (numbered 1-3 from west to east), and in clusters at inshore lumps. Inshore lumps are known to attract SBT for variable periods of time (Willis and Hobday 2007, Hobday and Campbell, in review).

The number of lines and receivers increased from 1 line of 20 receivers (Line 2, 2002-03) to 2 lines of 40 receivers (Line 1 and 2, 2003-04) and since 2004-05 has consisted of 70 listening stations in deployed in three lines and three lumps (**Figure 3)**. In addition, 3 stations were deployed at each of three lumps between the western and central lines (2004-05 to 2006-07). Water depth ranged from 55 m at the coast to 115 m at the furthest offshore station (water depth was ~170 m at the edge of this stations' detection range). Water depth at the inshore lumps averaged 52-59 m (**Table 1**). Stations were separated by approximately 1500 m, which was too large for complete acoustic coverage by the receivers. This spacing decision was based on a desire to cover the width of the shelf; a tag detection range of up to 450 m (for all models of tag) was expected based on detection experiments conducted while receivers were deployed (Hobday and Pincock in review). Stations were deployed to the edge of the continental shelf: validated trolling captures during the acoustic survey showed that age-1 SBT were restricted to the shelf in this region and time (**Figure 4)**.

The electronic releases on each listening station were programmed to activate after a specified interval. At this time the floats and acoustic receiver would float to the surface, still attached to the mooring anchors via polypropylene rope (**Figure 2)**. All parts of the listening stations were recovered using an attending vessel. Receivers were tested immediately after recovery to ensure that a test-tag could be detected and that the internal clock had not drifted. Data were downloaded using VEMCO software and results analyzed with custom software written in Matlab.

Acoustic tags (V8, V9 and V16, VEMCO) were activated and tested prior to deployment. These tags transmitted a coded pulse at a frequency of 69 kHz at random intervals every 20-60 seconds with a predicted lifetime of 365 days (V8) and 700 days (V16). The same protocol used for the capture and selection of SBT for conventional tagging (Williams 1983) was followed for the acoustic tagging (Hobday et al. 2001). In brief, fish were caught by poling or trolling at the stern of the vessel and then carried to a tagging cradle and length to caudal fork (LCF) measured. An acoustic tag was surgically implanted in the belly of each fish (see West and Stevens 2001) for an explanation of this procedure), which was also double tagged with conventional orange tags on each side just posterior to the second dorsal fin. The time from capture to release for each fish was under two minutes and all fish were tagged by a single experienced operator (AH).

The location of fish tagging varied each year due to the availability of fish (**Figure 5**). The general goal was to catch and release fish both inshore and offshore (shelf break), at lumps and away from lumps, and between the lines and to the west of the lines. Groups of 10-15 fish were preferred, although individual and smaller groups were released when more fish could not be captured – it is not easy to determine the number of fish that can be captured in a school ahead of time. The releases were predominately between Line 1 and Line 2, with the exception of 2006-07, where SBT were also released much further west (these western fish were excluded from some analyses presented here) (**Figure 5**). These western releases were to test specific hypotheses about movements from the west coast to the southern coast; however, 50 tags were still released between Lines 1 and 2 which allows comparisons with the previous years. When acoustically tagged fish passed close to a receiver, the identity, date and time, and if the tag contains a pressure sensor, the depth at the time was recorded on the receiver.

Data analyses

The acoustic data were used to estimate the following three factors from equation 2. Each factor can be estimated for each year the experiment was conducted, as outlined below.

Estimation of $D_{detection}$

The acoustic survey instruments (sonar and echosounder) have difficulty detecting SBT that were closer than 10 meters to the surface (Watanabe et al. 2004). Thus, the observed number of SBT should be corrected for the fraction too shallow to be encountered ($D_{detection}$). This detection estimate can range from 0% (all SBT were shallower than the detection depth) to 100% (all were deeper than the detection depth). The depth distribution of SBT in the survey area was derived from a limited set of tags that also had pressure sensors (VEMCO V16P, accuracy > 1 m). Each acoustic detection of such tags at a receiver was thus accompanied by a depth measurement. Aggregation of all the depth measurements provides an estimate of the total time spent at each depth. At this time, limited use of V16P tags in southern Western Australia has occurred, so to illustrate the estimation of $D_{detection}$ we also provide information collected with the same technology in the Great Australia Bight (Willis and Hobday 2007).

Estimation of $F_{offshore}$

To estimate the fraction of SBT passing within the acoustic survey box (**Figure 1a**), and hence could be encountered by the acoustic survey vessel, we used the pattern of detections at the cross-shelf lines. Fish could transit the cross-shelf lines on more than one occasion if they swam east and west; we used the total detections at each receiver as an indication of the amount of time all fish were spending at that distance from the coast. Because the number of lines changed between years, the estimates of $F_{offshore}$ may be biased between years. In this example, we show data for all lines to estimate a value of $F_{offshore}$ each year. The lines are divided into the inshore half and offshore half.

Estimation of $T_{residence}$

Residence time is important as an indicator of how long fish remained in the array area. The residence time calculations can be biased by the number of lines and receivers that were deployed in any year, and by the location of fish releases. For example, residence time can be calculated using Line 2 alone (used in 5 years), Line 1 and Line 2 (used for 4 years) or Line 1, Line 2, and Line 3 (used in 5 years), including or removing the inshore lumps. In this paper, we used detections at Line 2 only, to allow a 5-year time series of residence time to be constructed. We used half-life (*sensu* survival analysis) as an estimate of residence time. Here we define half life as the length of time at which half the tags detected in the study remain in the study area. The second element (T_{survey}) is not derived here, but can be obtained from the time the survey vessel takes to complete a transect replicate. Only fish released east of 118.2°E were included in the residence time analysis to ensure consistency between years.

Results

The deployment configuration for each year is shown in **Table 1**, with experiments lasting from 101 to 177 days. In general, the length of the experiment increased each year, as the mooring design improved and in order to ensure that all tagged fish had left the area when the experiment concluded. Between 59 and 130 SBT were tagged each year. The number of tags detected each year was in part due to locations in which fish were tagged. In 2005-06, over 80% of tagged fish were detected; however, they were all tagged between Line 1 and Line 2 (**Figure 2, Figure 5)**. In contrast, a lower overall percentage was detected in 2006-07; however, over 50% of the fish were tagged to the west of the array of receivers (**Figure 5E**).

Juvenile tuna implanted with the acoustic tags ranged from 43- 90 cm in length, with the mean size each year between 50.5 and 60.8 cm (**Table 2).** In four of the five years there was no difference between the size of tagged and detected fish (t-tests, $p<0.05$, **Table 2**). The final year (2006-07) showed a difference because small fish were tagged on the west coast, and only one of these fish was subsequently detected. These west coast fish were the same size as had been detected in previous years, and so this difference is likely due to migration, and not mortality.

Fish were detected throughout the experimental season, although the detections sharply declined or ceased by the end of each season. The total number of detections from all tags each year ranged between 261 and 28,023 (**Table 1)**, and forms a robust data for estimate of the key factors. The number of detections increased with the number of stations that were deployed, particularly the three years when receivers were deployed on inshore lumps.

Depth distribution - estimating $D_{detection}$

The depth distribution inferred from the acoustic tags with pressure sensors shows that juvenile SBT (age 1 and age-2) spend the majority (> ~70%) of time shallower than 10 m (**Figure 6)**. Thus, approximately 30% of fish would be detected in the sonar-based acoustic survey.

Inshore-offshore pathways – estimating $F_{offshore}$

The percentage of fish moving inshore or offshore through the survey area varied between years (**Table 3)**. In some years, the majority of tuna were detected at the inshore half of the receiver line (2002-03, Line 2, 68%), while the opposite was true in other years (2005-06, Line 2, 30%) (**Figure 7)**. There was also variation in the inshore/offshore fraction between lines in the same year (2005-06), indicating spatial variability in movement pathways. These differences were not consistent between years, suggesting that some other time variable factors, such as ocean conditions, may be important. This variation in the inshore-offshore detection of fish illustrates interannual variation in how fish use the southern Western Australia region.

Residence times – estimating $T_{residence}$

Residence time in the monitoring area varied by year (**Figure 8**, **Table 3**). Using detection of tagged SBT only at Line 2 to estimate half life, the half-life in the array area was only 11 and 19 days in 2002-03 and 2004-05, respectively. For the other three years, the half life was between 30 and 34 days. The movements of the fish from release locations to Line 2 are also shown in **Figure 8**, to illustrate the detection patterns.

Discussion

The calculation of an abundance index for juvenile southern bluefin tuna requires that either a constant fraction of fish occur within the survey area each year, or that the variation between years can be measured and accounted for. Evidence gathered using acoustic monitoring of tagged fish showed that the fraction of fish within the survey area varied between years, and should be accounted for when calculating an abundance index. Equation 2 showed how the index might need to be adjusted for three factors, the proportion of fish that can be detected based on the depth distribution by the survey methodology, the proportion of fish that move through the survey area, and the speed at which the fish move through the survey area.

A caveat with the use of depth data is that most of the detections of fish with V16P tags occurred around lumps (both Western Australia and GAB) (Willis and Hobday 2007). The acoustic survey took place away from lumps (which are a navigational hazard), and so future efforts to collect information on SBT depth distribution should concentrate on data collected as fish transit the open-water cross-shelf lines, as the depth distribution may differ in open water compared to around lumps.

Correcting the abundance estimate

Unfortunately the acoustic survey in southern Western Australia was halted in 2003, in part due to the costs of the survey, and the realization that there was potential variability in the estimated abundance index based on the correction factors (Itoh et al. 2005). Thus, calculation of an improved abundance index for the years of these acoustic monitoring experiments cannot be demonstrated. If interannual variation in the correction factors can be related to some additional variables, such as sea surface temperature, then post-hoc correction of the abundance index for the period 1995-2003 may be attempted. This analysis is underway, however, explaining interannual variation is likely to be difficult with only five years of data. The dramatic decline in the abundance index could be explained by inshore movement of fish, as observed in the first year of the acoustic experiment (68% of fish passed at the inshore half of the lines), if that pattern had occurred in some of the previous years. However, in subsequent years, with more fish being detected in the offshore half of the lines, the abundance index would have been expected to increase again. Unfortunately, by this time, the acoustic survey had been suspended.

Each of the correction factors will also have uncertainty associated with the estimates, which would also need to be included in estimating an overall abundance index. Accepted methods for calculating uncertainty for these tag data do not currently exist, and represent a challenge in utilizing data for management. Known issues include non-independence of detections, detection probabilities, and error propagation.

One additional complicating factor

In the austral summer of 2006/07, SBT were also tagged on the west coast of Western Australia. This was to examine the proportion of fish that move into southern Western Australia. Preliminary analysis shows that fish that were tagged on the west coast did not all move to the south coast. This suggests that not all the juvenile SBT population is in southern Australia during the austral summer. The southward movement of fish is likely to be assisted by the Leeuwin current (e.g. Lenanton et al. 1991), which has considerable interannual variation (Domingues et al. 2007; Waite et al. 2007). Thus, it is reasonable to presume that the proportion of SBT moving in southern Western

Australia may also vary between years and the equation for estimating the N_{fish}, is suggested to be better represented as;

$$N_{fish} \approx E_{fish} \bullet D_{detection} \bullet F_{offshore} \bullet T_{survey}/T_{residence} \bullet M_{pathway} \quad (3)$$

where $M_{pathway}$ is the fraction of fish that migrate through southern Western Australia. This of course, further complicates the generation of an abundance index for age-1 SBT. Thus, the next step is to understand the fraction of fish that move through southern Australia, from the west coast of Australia. This is a major uncertainty, which will impact other population assessments for this species. While the acoustic survey to generate an abundance index has been suspended indefinitely, these results may also be applicable to other more cost-effective survey methods being attempted in southern Western Australia (Itoh et al. 2005; Itoh 2007), and in the case of $M_{pathway}$, to the estimation of SBT abundance in the Great Australia Bight (Cowling et al. 2003; Eveson et al. 2007).

The purpose of this paper has been to illustrate how information gathered using electronic tags, as part of an acoustic monitoring experiment, can improve abundance estimates needed for sustainable fisheries management. The results presented here indicate that estimates of residence time, migration pathways, and habitat use can be derived from acoustic tag data. These factors are in turn important in correcting an abundance index for juvenile SBT. The value of five years of data is apparent given the interannual variation in these factors, and effort must be made to continue these time series into the future.

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References

Caton, A.E. (1991) Review of aspects of southern bluefin tuna biology, population and fisheries. In: Shomura RS, Majkowski J, Langi S (eds) Proceedings of the first FAO Expert Consultation on interactions of Pacific tuna fisheries. Noumea, New Caledonia, p 296-343.

CCSBT (2007) Report of the Twelfth Meeting of the Scientific Committee. Available from http://www.ccsbt.org/docs/meeting_r.html

Cowling, A., Hobday, A. J. and Gunn, J. (2003) Development of a fishery-independent index of abundance for juvenile southern bluefin tuna and improvement of the index through integration of environmental, archival tag and aerial survey data. CSIRO Marine Research. FRDC Final Report 96/118 & 99/105.

Domingues, C.M., Maltrud, M.E., Wjiffels, S.E., Church, J.A., and Tomczak, M. (2007) Simulated Lagrangian pathways between the Leeuwin Current System and the upper-ocean circulation of the southeast Indian Ocean. *Deep-Sea Res II* **54**, 797-817.

Farley, J.H., and Davis, T.L.O. (1998) Reproductive dynamics of southern bluefin tuna, *Thunnus maccoyii*. *Fish. Bull.* **96**, 223-236.

Gunn, J.S., Davis, T.L.O., Polacheck, T., Betlehem, A., Sherlock, M. (1995) The application of archival tags to study SBT migration, behavior and physiology 1995 Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/95/8. CSIRO Marine Laboratories Hobart

Eveson, P., Bravington, M. and Farley, J. (2007) Aerial Survey: updated index of abundance and preliminary results from calibration experiment. CCSBT-ESC/0709/12. Available from http://www.ccsbt.org/docs/meeting_r.html

Heupel, M.R., Semmens, J.M., and Hobday, A.J. (2006) Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. *Mar. Freshw. Res.* **57**, 1-13.

Hobday, A.J. (2002) Acoustic monitoring of SBT within the GAB; exchange rates and residence times at topographic features. Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/02/03. CSIRO Marine Research, Hobart, Australia.

Hobday, A.J. (2003) Nearshore migration of juvenile southern bluefin tuna in southern Western Australia, Southern Bluefin Tuna Recruitment Monitoring Workshop Report. RMWS/03/15. CSIRO Marine Research, Hobart, Australia.

Hobday, A.J., Davis, T.L.O., Gunn, J.S. (2001) Determination of SBT residence time via acoustic monitoring along the southern WA coast. Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/01/05. CSIRO Marine Research, Hobart, Australia.

Hobday, A.J., and Hartmann, K. (2006) Near real-time spatial management based on habitat predictions for a longline bycatch species. *Fish. Manage. Ecol.* **13**, 365-380.

Hobday, A. J. and D. Pincock (in review) Estimating detection probabilities for linear acoustic monitoring arrays. *Can. J. Fish. Aqu. Sci.*

Hobday, A.J. and Campbell, G. (in review) Topographic preferences and habitat partitioning by pelagic fishes in southern Western Australia. *Mar. Freshw. Res.*

Hobday, A.J., Flint, N., Stone, T., and Gunn, J. S. (in review) Electronic tagging data supporting flexible spatial management in an Australian longline fishery. In J. Nielsen (ed). Electronic Tagging and Tracking in Marine Fisheries II. Reviews: Methods and Technologies in Fish Biology and Fisheries.

Itoh, T., and Tsuji, S. (2004) Review of Acoustic Monitoring Survey - Analyses of data for eight years. Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/04/03. CSIRO Marine Research, Hobart, Australia.

Itoh, T., Takao, T., and Tsuju, S. (2005) Proposal of RMP surveys in WA for age one southern bluefin tuna in 2004/2005. Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/05/16. CSIRO Marine Research, Hobart, Australia.

Itoh, T. (2007) Some examination on the recruitment index of age 1 southern bluefin tuna derived from the trolling survey.CCSBT-ESC/0709/35. Available from http://www.ccsbt.org/docs/pdf/meeting_reports/ccsbt_14/report_of_SC12_public_version.pdf

Lenanton, R.C., Joll, L., Penn, J., and Jones, K. (1991) The influence of the Leeuwin Current on coastal fisheries of Western Australia. *J. Royal Soc. West. Aust.* **74**, 101-114.

Musyl, M.K., Brill, R.W., Curran, D.S., Gunn, J.S., Hartog, J.R., Hill, R.D., Welch, D.W., Eveson, J.P., Boggs, C.H., and Brainard, R.E. (2001) Ability of archival tags to provide estimates of geographical position based on light intensity. In Sibert J.R., Nielsen J.L. (eds) Electronic Tagging and Tracking in Marine Fisheries. Kluwer Academic Publishers, London, p 343-367

Polacheck, T. (2002) Experimental catches and the precautionary approach: the Southern Bluefin Tuna dispute. *Mar. Pol.* **26**, 283-294.

Watanabe, K., Takao, Y., Sawada, K., Abe, K. (2004) Acoustic survey of pelagic fishes using a side-scan sonar, preliminarily operated for the coming SBT survey. Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/04/04. CSIRO Marine Research, Hobart, Australia.

Teo, S.L.H., Boustany, A., Blackwell, S., Walli, A., Weng K.C., and Block, B.A. (2004) Validation of geolocation estimates based on light level and sea surface temperature from electronic tags. *Mar. Ecol. Prog. Ser.* **283**, 81-98.

Waite, A.M., Thompson, P.A., Pesant, S., Feng, M., Beckley, L.E., Domingues, C.M., Gaughan, D., Hanson, C.E., Holl, C.M., Koslow, T., Meuleners, M., Montoya, J.P., Moore, T., Muhling, B.A., Paterson, H., Rennie, S., Strzelecki, J,. and Twomeya, L. (2007) The Leeuwin Current and its eddies: An introductory overview. *Deep-Sea Res. II* **54**, 789-796.

Welch, D.W., and Eveson, J.P. (1999) An assessment of light-based geoposition estimates from archival tags. *Can J Fish Aquat Sci* **56**, 1317-1327.

West, G.J., and Stevens, J.D. (2001) Archival Tagging Of School Shark, Galeorhinus Galeus, in Australia: Initial Results. *Env. Biol. Fish.* **60**, 283-298.

Williams, K. (1983) Big numbers of SBF tuna tagged off Esperance. *Australian Fisheries* July: 26-27.

Willis, J., and Hobday, A.J. (2007) Influence of upwelling on movement of southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight. *Mar. Freshw. Res.* **58**, 699–708.

Table 1. Summary of the experiments for the acoustic experiment in southern Western Australia. IL = inshore lumps. See **Figure 3** for locations of the lines.

Year	Number of lines (receivers)	Tags deployed	Experiment start date	Length of experiment (days)	Tags detected (%)	Total detections
2002-03	1 (20)	73	Dec 3, 2002	101	32.9	261
2003-04	2 (40)	59	Dec 3, 2003	117	49.2	443
2004-05	3 (61) + 3 IL (9)	79	Dec 4, 2004	102	69.6	28,023
2005-06	3 (61) + 3 IL (9)	81	Dec 2, 2005	160	84.0	5,214
2006-07	3 (61) + 3 IL (9)	130	Dec 1, 2006	177	48.5	18,514

Table 2. Summary of the size of the tagged and detected southern bluefin tuna in southern Western Australia over five years of acoustic experiments (N = no, Y = yes).

Year	Acoustic tags deployed (n)	Mean size of all fish tagged (cm)	Mean size of all fish detected (cm)	Difference between tagged and detected sizes (t-test, $p < 0.05$)
2002-03	73	60.8	59.8	N
2003-04	59	57.8	55.6	N
2004-05	79	51.4	53.5	N
2005-06	81	49.3	49.6	N
2006-07	130	50.5	57.9	Y

Table 3. The percentage of tagged southern bluefin tuna detected in the offshore half of each line of receivers. Percentages less (greater) than 50%, indicate that fish were passing using a predominately inshore (offshore) pathway. Residence time, based on detections at Line 2 and releases east of 118.2°E, is shown in the final column, together with the number of detected tags and individual detections on which the residence time was based.

Year	Line 1 (%)	Line 2 (%)	Line 3 (%)	Average of all lines (%)	Movement pathway	Residence time (days) (n tags, n pings)
2002-03	-	32	-	32.0	Inshore	11 (n = 19 & 226)
2003-04	42	45	-	43.5	Inshore	34 (n = 24 & 221)
2004-05	39	27	6	24.0	Inshore	19 (n = 27 & 575)
2005-06	21	70	73	54.6	Offshore	30 (n = 27 & 2118)
2006-07	44	38	61	48.0	~Equal	34 (n = 23 & 438)
Average	36.5	42.4	46.7	40.4		25.6 days

Figure Legends

Figure legends are repeated on each figure to aid the review process

Figure 1. **A**. Ship-based acoustic survey area for southern bluefin tuna (blue polygon) in southern Western Australia and sea surface temperature for an example summer, showing the influence of the Leeuwin Current (warm water from the west). **B**. Abundance index for juvenile southern bluefin tuna in the survey area, derived from the ship-based acoustic survey. The year (e.g. 1996) refers to the austral summer (e.g. 1995/96).

Figure 2. Configuration of listening station moorings during the sub-surface deployment period (left) and ready for recovery (right).

Figure 3. Locations of listening stations in the southern bluefin tuna acoustic monitoring experiment in southern Western Australia. The acoustic survey area is inside the blue polygon, the dashed line represents the outer boundary of the survey in the years 2002-03. The years in which listening stations were deployed at these lines and inshore lumps is described in the text.

Figure 4. Locations of southern bluefin tuna detected by trolling in the acoustic survey (1995-2003). The size of the marker refers to the number of individual fish captured by trolling at a location. The location of the 200 m contour is shown.

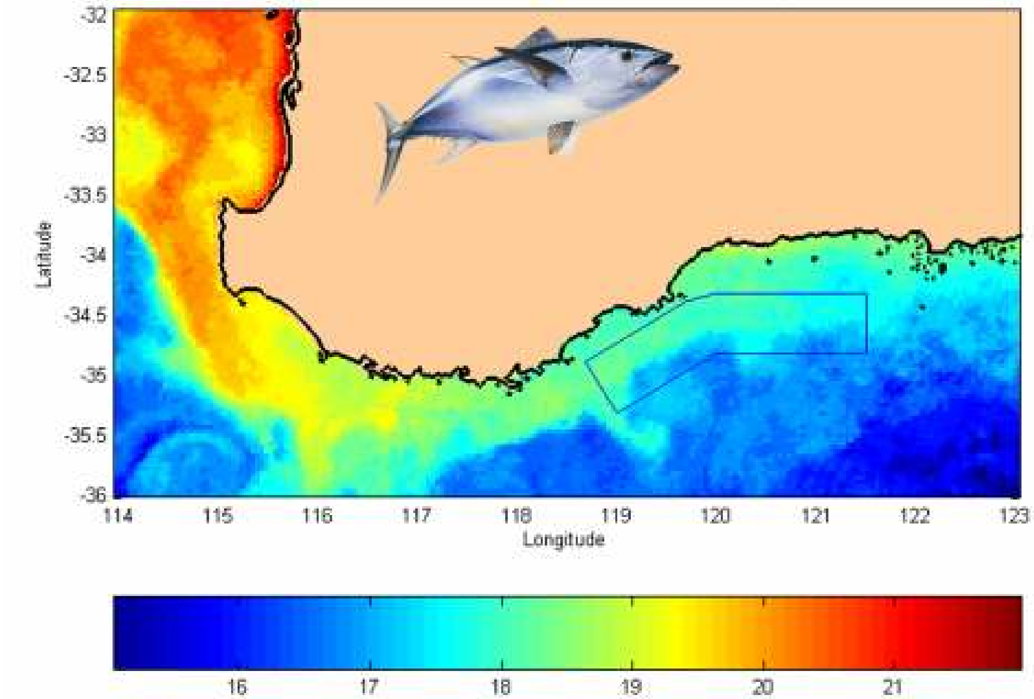
Figure 5. Release locations for acoustically tagged southern bluefin tuna (red stars), together with the location of receivers for that year **A**. 2002-03 (n = 73 tags). **B**. 2003-04 (n = 59 tags). **C.** 2004-05 (n = 79 tags). **D.** 2005-06 (n = 81 tags). **E**. 2006-07 (n = 130 tags, but 50 tags east of 118.2°E).

Figure 6. Estimation of the depth distribution of southern bluefin tuna derived from acoustic tags with a pressure sensor. **A**. A single fish in southern Western Australia. **B**. Depth distribution for SBT based on acoustic tags in the Great Australian Bight (from Willis and Hobday 2007).

Figure 7. Cumulative frequency plots of detection of acoustically tagged southern bluefin tuna across each line of receivers. **A**. Line 1, deployed for four years. **B.** Line 2, deployed for five years. **C**. Line 3, deployed for three years. The 1:1 line at 45 degrees shows the cross-shelf distribution that would be observed if fish passed the cross-shelf line at random distances across the continental shelf. For example, consider 2005 for Line 3: only 10% of detections were made offshore of station 50, thus 90% are inshore. See text for full interpretation.

Figure 8. Residence time and movements of SBT detected in the acoustic monitoring study. Left hand column shows the number of fish remaining to be detected as a function of time since each fish was released. **A.** 2002-03, **B.** 2003-04, **C.** 2004-05, **D.** 2005-06 and **E.** 2006-07. The half life is indicated by the vertical black line (numbers provided in **Table 3)**. The right hand column indicates the tracks of fish from their release point (circles), when only Line 2 detections (cross-shelf line) and releases east of 118.2°E are used. **F.** 2002-03, **G.** 2003-04, **H.** 2004-05, **I.** 2005-06 and **J.** 2006-07. The acoustic survey box is indicated by the blue polygon. 1 degree of longitude represents approximately 100 km at this latitude.

A.



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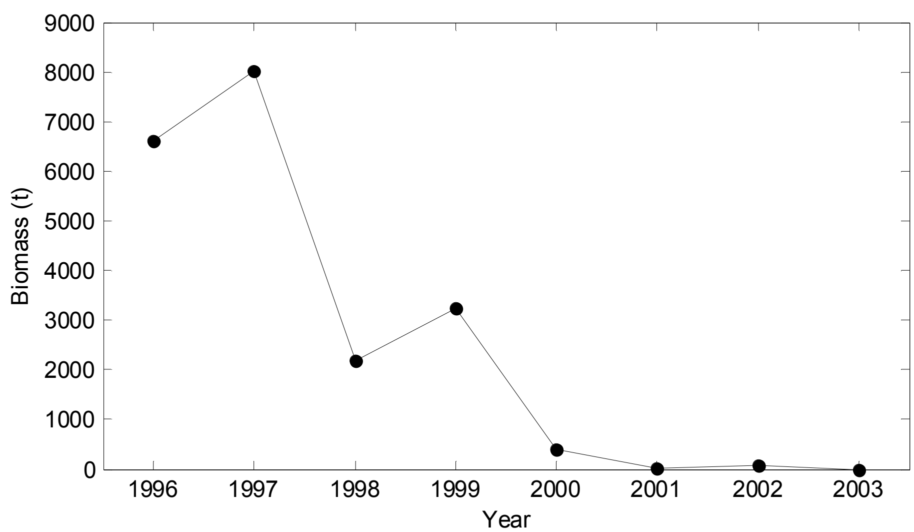

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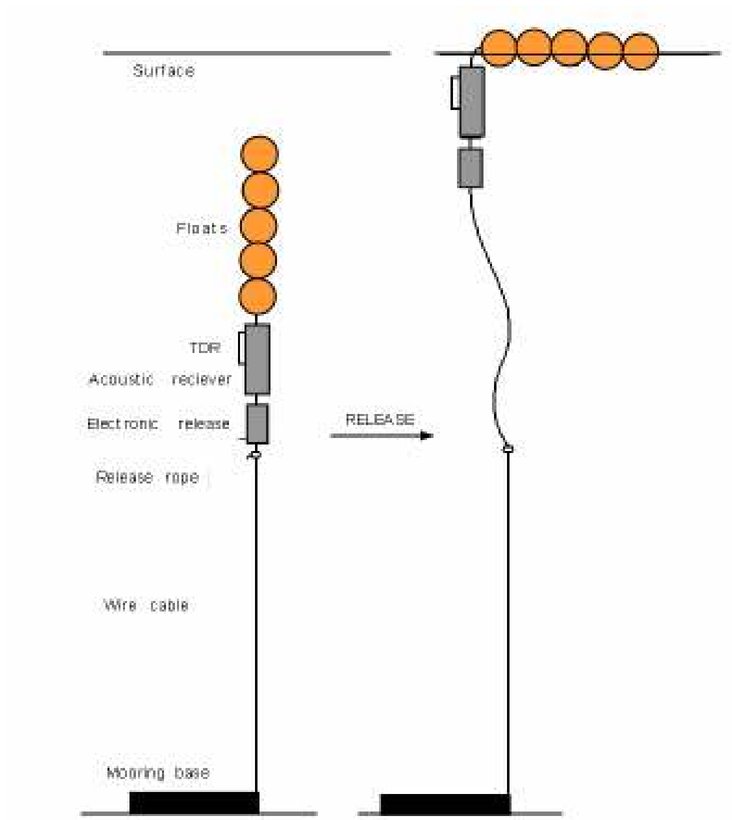

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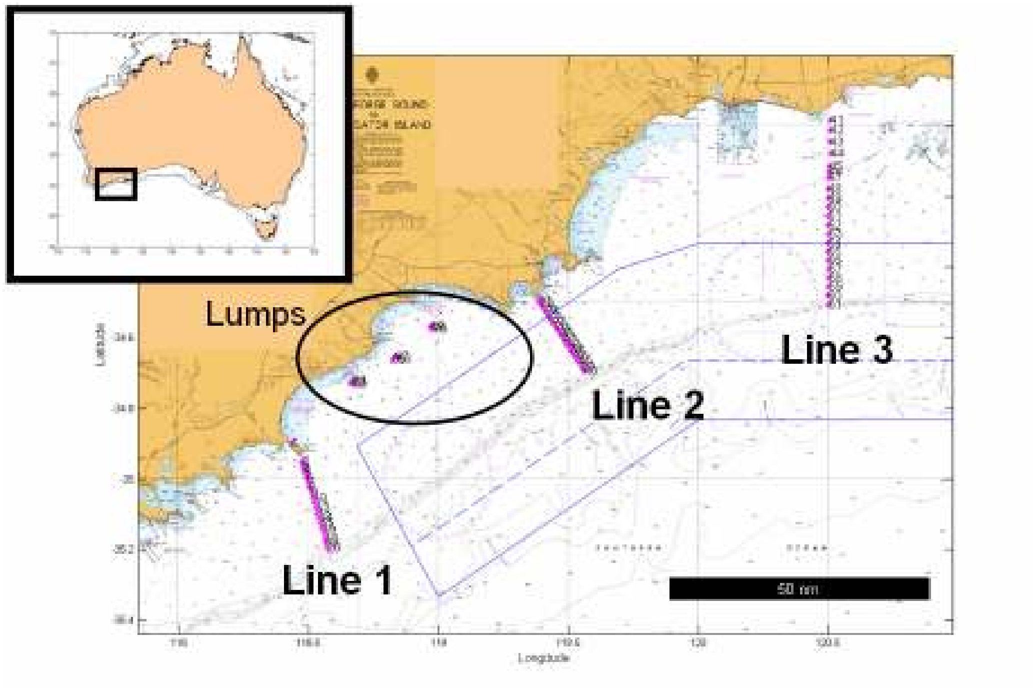

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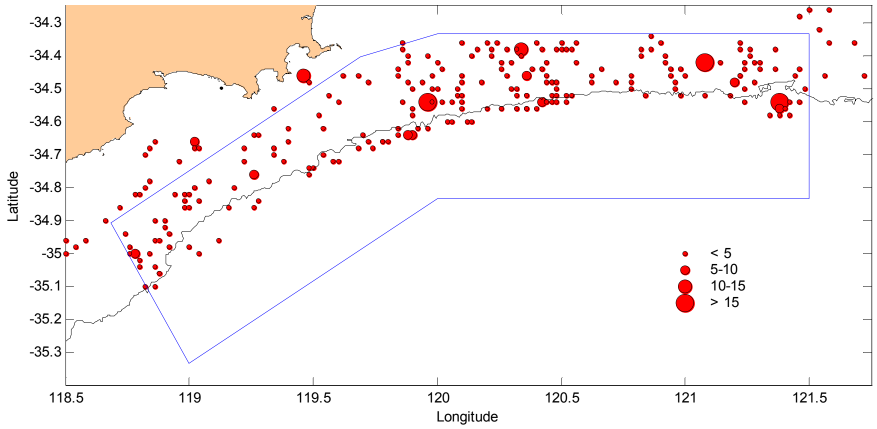

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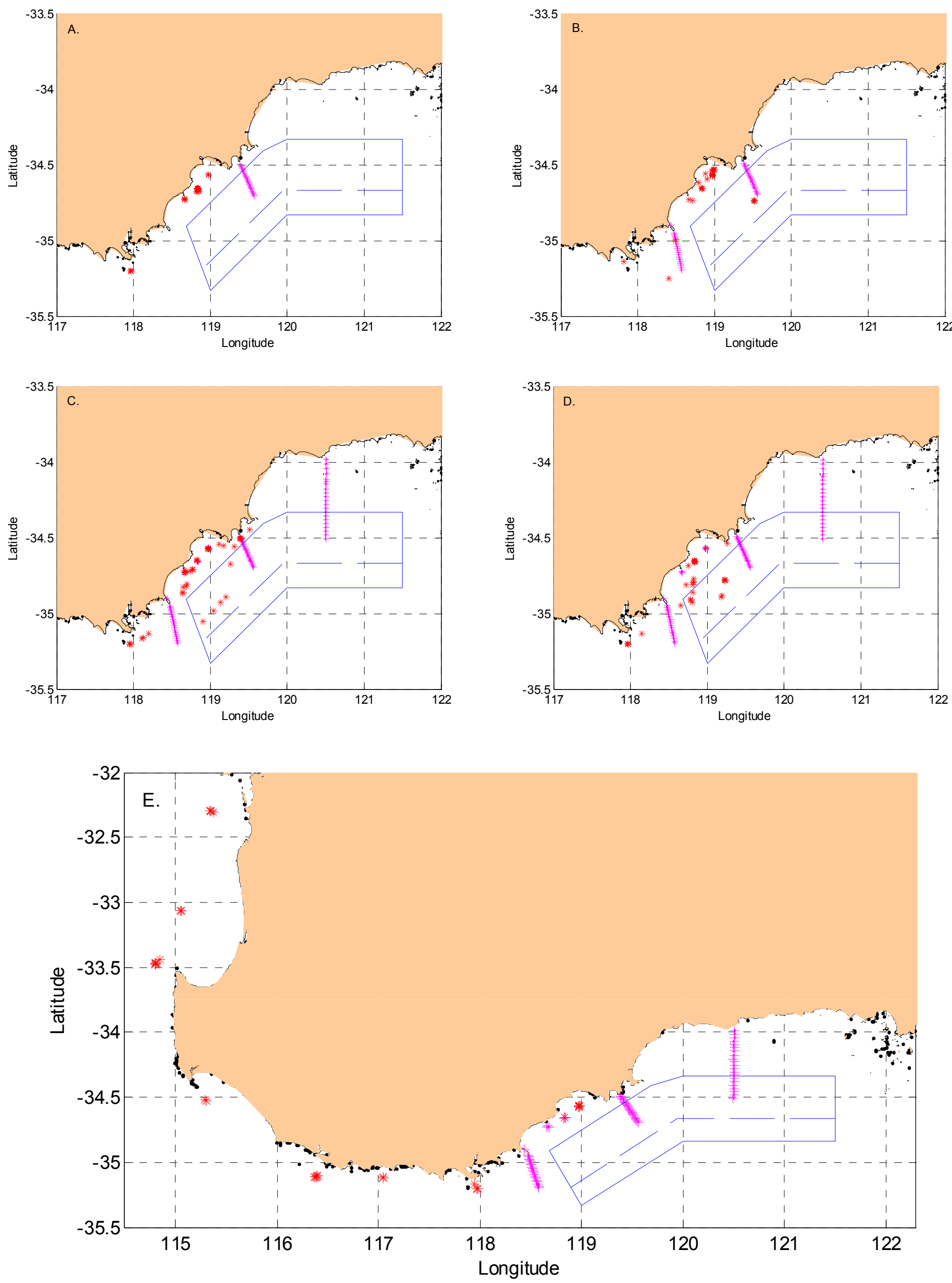

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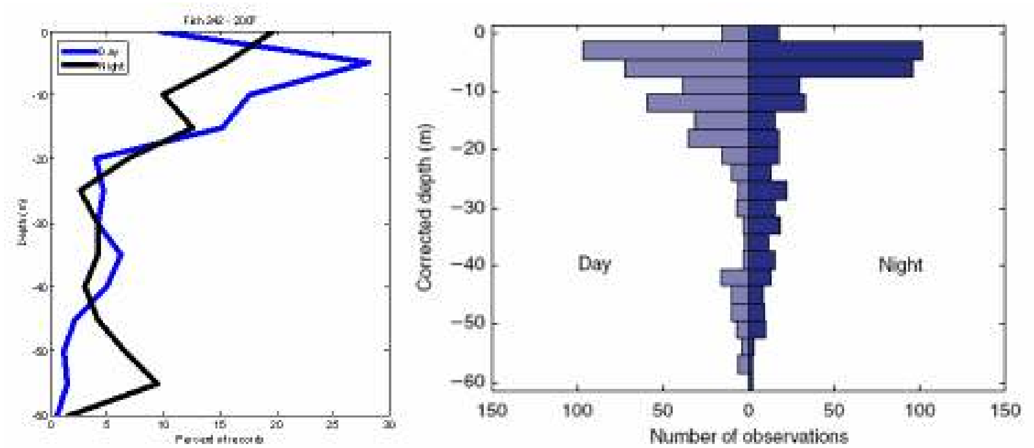
A. B.



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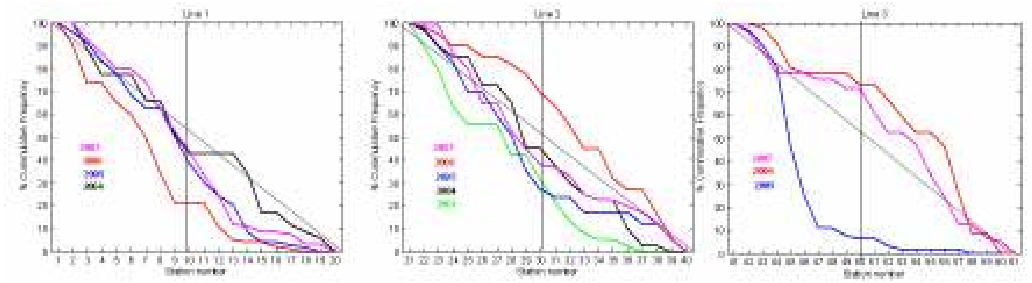
A. B. C.



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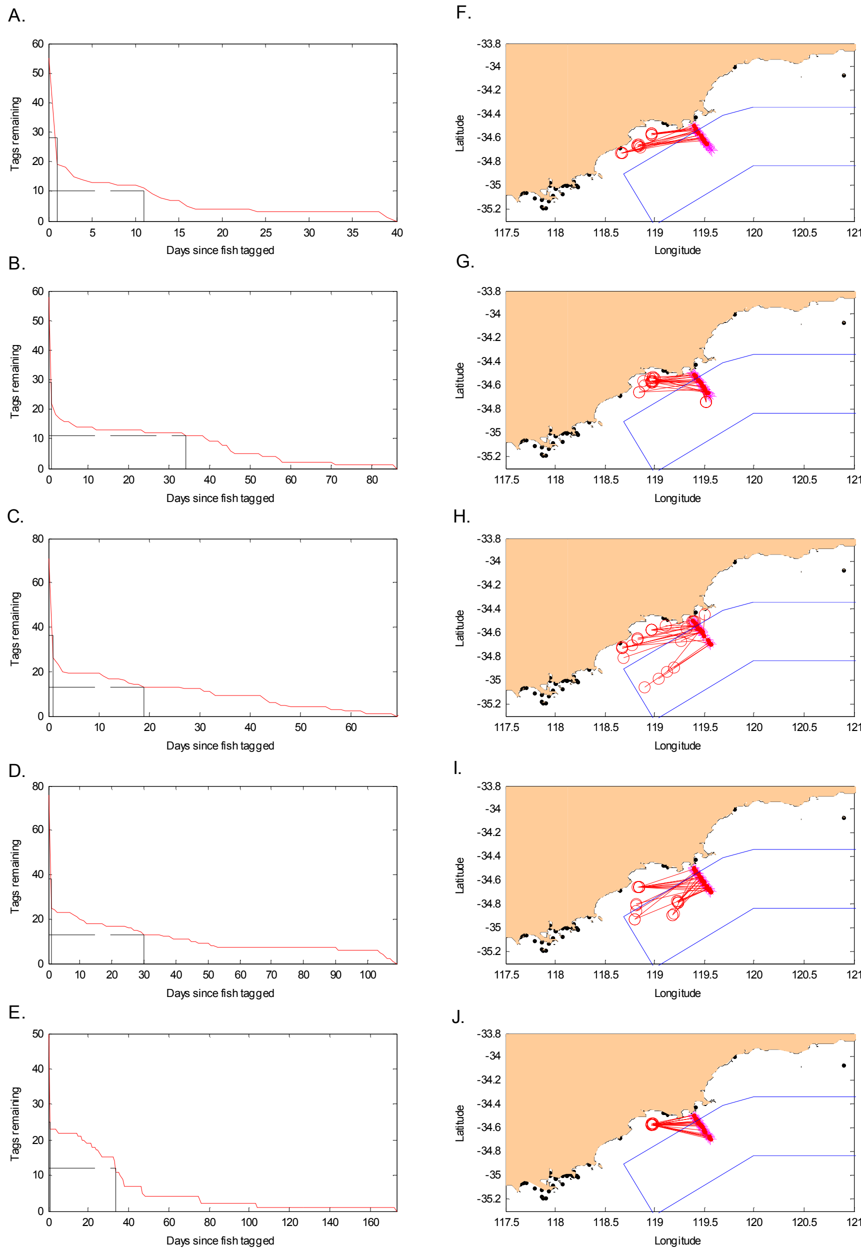

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