SCIENTIFIC COMMITTEE
NINTH REGULAR SESSION

Pohnpei, Federated States of Micronesia
6-14 August 2013

Analyses of tagging data for tropical tunas, with implications for the structure of WCPO bigeye stock assessments

WCPFC-SC9-2013/SA-IP-06

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Exec summary

The 2012 review of the 2011 Western and Central Pacific (WCPO) bigeye assessment recommended (among other things) analyses of the influence of tagging data on the bigeye stock assessment, recommending that some tag release groups should be dropped or the spatial structure should be re-examined. This document represents an update on a number of ongoing analyses intended to explore these and related issues. We considered bigeye tagging in the 1989-1992 RTTP and the 2005-2013 PTTP in some detail, and also include skipjack and yellowfin data for comparison. In addition to describing the general nature of the bigeye assessment sensitivity to the tagging data, we attempt to i) quantify how various factors influence tag displacement, ii) quantify how tag density (tags/catch, a measure of tag mixing) varies spatially, and iii) illustrate how key inferences from bigeye and yellowfin tuna stock assessments change with the selected exclusion of different tag release areas. A parallel paper (Kolody and Hoyle 2013) applies statistical tests to evaluate whether tags mix with the untagged population at a rate that is consistent with assessment model assumptions. The analyses undertaken suggest that the following areas of research warrant further examination.

1. Develop methods to apply revised weightings to the tag likelihood, and to estimate reporting rate priors that appropriately reflect the information in the tag data, so as to include Region 4 tags in the model with appropriate levels of influence. Longer term, simulation is needed to estimate appropriate weighting. Shorter term we would compare tag densities with alternative biomass distribution hypotheses, estimate their implications for tag likelihood weight and RR priors, and explore the sensitivity of the model to these alternatives.

2. Given the impact of the tagging data on the assessment results, and while work is being done to better model these data, we recommend a parallel investigation of the impact of other data sources in the BET assessment, using models with more influential tagging data excluded. For example, parts of previous sensitivity analyses (e.g. Harley *et al.* 2010; Hoyle *et al.* 2008) should be repeated without the masking effect of the biomass ceiling imposed by reporting rate parameters that are estimated at the upper boundary. We estimate 3 months work.

3. Explore alternate spatial constructions of MFCL that may better meet the assumptions of tag mixing. Apply the analyses outlined in Kolody and Hoyle (2013) and Kolody and Hoyle (submitted) (i.e. CPRD and SVTD analyses) to inform these structures. We estimate 4 months work.

4. Develop a tag simulator (potentially using SEAPODYM) to allow explicit modelling of finer resolution movement of tuna to estimate the errors in our estimates of fishing mortality, natural mortality, movement and abundance that might arise from the failure to fully satisfy tag mixing assumptions. We estimate that this would involve 12-18 months work.

5. Evaluate the implications of the link between EPO and WCPO fish. Develop a method for inclusion/modelling of central pacific fish and tags migrating into the EPO, and vice versa. This may involve including EPO tags and catch in a separate region to the east that is not included in biomass calculations.

6. Estimate horizontal movement tracks from all available archival tags for the western and central Pacific Ocean to parameterise how size influences movement rates, and to examine whether effort distributions (and reporting rates) are biasing perceptions of movement based on conventional tags. We estimate that the size analysis could be completed within 3 months by restricting inferences to longitude.

7. Explore the option of excluding tag recoveries from the likelihood for fishing mortality and biomass, but retain them for estimation of movement rates through the use of a tag likelihood conditional on tag recapture rather than on catch. This was also recommended by the bigeye review panel.

We suggest the following key priorities for the next bigeye assessment model:

1. The prior distributions on the reporting rates, which are currently estimated by analysing tag seeding data, should be reconsidered to take into account uncertainty in mixing assumptions not included in the tag likelihood, and uncertainty in the associated catches not included in the catch likelihood (i.e. uncertain species composition estimates), as well as in the reporting rates themselves (e.g. the possibility that they vary through time).

2. Tag reporting rate parameters estimated on and constrained by the upper boundary can have a large influence on models. The model should be structured to ensure that this does not happen for the wrong reasons. The plausibility and implications of such an outcome should be carefully examined in future assessments.

3. Tag data should not be given undue weight in the assessment, given that their implications for the assessment are uncertain under the current regional configuration, particularly in regions 3 and 5. Solutions will be explored using SVTD analyses and simulation. Given the variation in tag density within region 3, we recommend giving these tags little weight in the assessment until we can determine the implications of incomplete tag mixing. Similarly, given the many long-term recaptures from very similar locations in region 5, and their effects on the assessment conclusions, we recommend omitting these relatively few tags from the assessment until the model's necessary simplifying assumptions can be reconciled with the potentially complex behaviour of these bigeye.

4. Conflicts between information provided by the tagging data, other data in the model, and key assumptions should always be investigated, and if they cannot be resolved they should be included in the structural uncertainty of the assessment.
5. Given that bigeye purse seine catch estimates are uncertain in some areas and periods, consider loosening catch deviate penalties or even setting catch to missing so that tag returns are predicted with appropriate levels of uncertainty.

Introduction

In 2012 the WCPFC commissioned a review of Davies *et al.* (2011); "Stock assessment of bigeye tuna in the WCPO". The bigeye review (Ianelli, Maunder, & Punt 2012) made a number of recommendations, with the following two recommendations directly addressing methods for modelling bigeye tagging data in MULTIFAN-CL.

Recommendation 7: To better address the assumption of homogeneity in tag-recapture data, split Region 3 into two regions and examine whether Region 5 should be split into two regions for tagging off eastern Australia.

Recommendation 13: Drop the region 5 tagging data unless the model can be re-structured to make the area where the Australian tagging took place in region 5 a separate region.

This paper seeks to address these recommendations to provide advice for future modelling of tagging data in bigeye stock assessments. Parallel analyses are carried out for yellowfin and in some cases skipjack tuna, both for contrast and to facilitate future yellowfin and skipjack assessments. SPC agreed with the first recommendation (WCPFC 2012) and responded to the second as follows: "Agree. Drop or consider spatial restructuring instead. We also plan to carefully examine tagging data and model fits for both recent and historical tagging to determine if other issues exist. This will be complemented with analyses of mixing rates to determine the best way to model tagging data."

This paper describes the background to these recommendations, and presents analyses designed to identify better approaches for modelling the tagging data. Modelling the tagging data appropriately requires an understanding of how these data are used in MULTIFAN-CL. We describe this in some detail, and provide preliminary exploration of the possible effects of incorrect assumptions.

The WCPO bigeye stock assessment currently includes data from three tagging programs; the Regional tuna tagging programme (implemented between 1989-1993) (Kaltongga 1998); Coral Sea tagging (1995-2001) (Hampton & Gunn 1998); and the Pacific tuna tagging programme (2006-today) (Caillot et al. 2012).

Background

Tag mixing

An important assumption in MULTIFAN-CL stock assessments is that all fish (of a particular age-class) within a region are part of a common pool; i.e. removing fish from one part of the region has the same effect on the population as removing fish from another part of the region. Similarly when tagging data are included it is assumed that tagged and untagged fish are equally vulnerable to fishing. This mixing assumption is standard in mark-recapture modelling. In practical terms this means that all tags in a region are assumed to be distributed through the population (of the same age classes), so that catch at size from any part of the region has the same chance of including tagged fish as fishing in any other part. Mixing is required because fishing effort varies spatially and temporally in unpredictable ways, and the population distribution at size also varies unpredictably through time and is never accurately known. One caveat to this assumption is that, even if mixing is not complete, biases due to lack of mixing may coincidentally cancel each other out, if too many tags are caught in one area and too few are caught in another area, so that overall the correct number of tags is captured. This is more likely if release groups are distributed, on average over a tagging programme, at random with respect to the population. However, we cannot determine whether this has occurred since we do not know the spatial distribution of the vulnerable population through time.

The MULTIFAN-CL regions used in the stock assessment of bigeye tuna are very large (from east to west region 3 is 5600km, and region 4 is 4400 km) and although bigeye are highly mobile animals it is possible that tagged bigeye will take a long time to fully mix within the population of a region (and there could be individual spatial preferences that prevent them ever mixing completely). Until tags are fully mixed, the proportions of fish that are tagged will vary across the region and given the non-random spatial distribution of effort, unmixed tagged fish have different vulnerability to fishing from untagged fish. For this reason, recaptures of recently-released tags are omitted from likelihood calculations until mixing is assumed to be complete. Tag mixing for the bigeye and yellowfin stock assessments is assumed to be complete (within the release region) 2 quarters after release (3-6 months), and 1 quarter (0-3 months) for skipjack. A fish that moves across a boundary after the initial mixing period into another region is assumed to be immediately fully mixed within that region.

It is important to note that tagged bigeye are only in the proportion of the population vulnerable to the main PS fishery for a short period. Most fish tagged in the equatorial region are small (age classes 2-6 quarters) and most of the recoveries are from the FAD fishery, which selects mostly age classes 4-6. Most of the tagged fish will probably grow through the vulnerable age range within 4 quarters. Unless a very large number of individuals are tagged, it is desirable to have a reasonably short mixing period to ensure there sufficient recoveries to be informative.

Assuming that unmixed tags are mixed will affect the estimates of population dynamics. In a simplified form the population size *N* is estimated as $\widehat{N} = \frac{T_1 C_2}{m_2}$, given T_1 tagged fish in the population, a catch of C_2 fish, and observation of m_2 tagged fish in that catch. Similarly, fishing mortality *F* is calculated as $\widehat{F} = \frac{C_2}{N} = \frac{m_2}{T_1}$ (the assessments discussed here use the Baranov-exponential form of the catch equation, but the principle is the same). When fishing pressure is higher where tags are denser than average, a disproportionately large number of tags are captured, which biases *F* estimates high and *N* estimates low. Conversely, fishing where tags are less dense than average will result in disproportionately fewer tags being caught, and will bias F low and N high.

For example, in Figure 1, tagged skipjack that were released in area R3 were recaptured in the marked positions (circles) 1 quarter after release. The distribution of the catch is shaded, and the inferred tag density (tags / catch) is shown in the contour lines. The tags are not well mixed. Since the high catch areas have below-average tag density, this experiment would catch fewer tags than expected, and (if permitted to contribute to the likelihood) tend to bias F low and N high.

Information about F and N enters the stock assessment from a number of sources, because the stock assessment software MULTIFAN-CL (Fournier, Hampton, & Sibert 1998) uses integrated analysis (Fournier & Archibald 1982;Maunder & Punt 2012) to combine information from different datasets. The recaptures in each fishery contribute to the model results, as does information from CPUE, total catches, size data, and the biological parameters that make up the model.

Reporting rates

Reporting rates are another important component of the assessment, and they interact directly with the tagging data. Not all captured tags are reported, and MULTIFAN-CL estimates a reporting rate (RR) between 0 and 0.9 for each fishery and tagging program (Figure 2). In the assessment, it is assumed that RR is stationary for each fishery (for each tagging programme) and uniform within each spatial region. Adding RR to the equation $N=T_1 . C_2/m_2$ gives $N = T_1 . C_2 . RR/m_2$. Catch C_2 and tags released T_1 are generally well known and close to being fixed, but RR and *N* are estimated. This means that RR's directly interact with estimates of F and N, via the tagging data. In simple terms, a lower reporting rate implies more tag recoveries, which in turn implies lower N and higher F (than would be estimated if it was assumed that all tags were reported). All other things being equal, the reporting rate (RR) is directly proportional to N and inversely proportional to F.

For some RRs we have estimates from tag seeding experiments, in which case we impose this estimate as an informative prior distribution – the shorter grey stripes in Figure 2. MULTIFAN-CL estimates all RRs whether or not they have informative priors. In Figure 2, each black dot represents an estimated RR.

When more tags are observed for a fishery and tagging program than expected, the tag component of the likelihood will favour a higher RR; just as fewer tags than expected will favour a lower RR. If there is a prior distribution on the RR, there may be a difference between the number of tags expected and the numbers observed. The model will try to reduce this difference, which may change the parameter estimates. In other words, the model will try to predict more tags by lowering the biomass estimate, or changing some other parameter, in order not to move the RR too far from the prior. Problems arise if the excess observations are caused by a failure of the model assumptions, such as when the proportion of tags in the catch is different from the proportion in the regional population. Note that since the model 'uses' the reporting rate to account for differences between the expected and observed numbers of tag recoveries, the effects of the RR cascade through the model. The RR can effectively be a proxy for multiple factors including uncertainty about tag mixing and errors in catch estimates. These issues should be considered when estimating the prior distribution on RR.

When MULTIFAN-CL is fitted to data that includes a lot more tag returns than it predicts, the RR can hit the upper boundary (RR's 3 and 25 in Figure 2, labelled in red), which acts analogously to a strong prior. The upper limit to the RR at 0.9 can place an upper limit on the biomass estimate, particularly when a lot of tags are involved. It is possible that a fishery could have real reporting rates approaching the upper bound, but if the high RR is an artefact of inadequate tag mixing, the biomass could be under-estimated in a manner that is not obvious in the model diagnostics.

Model runs undertaken as part of the WCPO bigeye stock assessment review indicated that past bigeye assessments may have been affected by this problem. Many of the tags released during the RTTP and Coral Sea tagging programs in region 5 of the bigeye assessment were recaptured in the same Region (Figure 3) in the local Australian longline fishery (fishery 11, Figure 4). Reporting rates for this fishery and for the two tagging programs (RR 3.RTTP_R5_LL-AU and RR 25.Coral_Sea_R5_LL-AU) were estimated at the boundary of 0.9, which resulted in a large difference between the observed (blue diamonds in Figure 4) and expected (brown line) tags. The likelihood favours low population numbers in region 5 in an attempt to fit the large numbers of tag recoveries. Region 5 is a numerically small region in the assessment, but the abundance estimate in region 5 during a defined period (1960–86) is linked to the abundances in other regions by a shared catchability parameter for longline fleets (i.e. relative abundance is assumed to be proportional across regions). The relative abundances, estimated using regional scaling methods (Hoyle & Langley 2007;Langley et al. 2005), are based on analyses of longline CPUE by region (Figure 5). Constraints on region 5 abundance therefore affect the abundance estimates in every other region.

The observation that reporting rates were on the 0.9 boundary aroused suspicion that the bigeye tagged in region 5 during the RTTP and CS tagging programs might not be mixing as expected by the model assumptions. This is consistent with plots of displacement versus time at liberty (Hampton, Lewis, & Williams 1997), which show small observed displacements even after long periods at liberty of over 5 years (Figure 6-Note however, that Figure 6 on its own may mislead, in the sense that observed displacements are not necessarily representative of all tag movements (because observations are dependent on fishery selectivity, spatial distribution of effort and reporting rates). Some fish tagged in region 5 left the tagging location and subsequently returned to the same location, suggesting the possibility of seasonal migration (Evans et al. 2008;Hampton & Gunn 1998).

We investigated the distributions of tagged bigeye and their effects on the stock assessment in several different ways. Firstly, we investigated factors affecting displacements between release and recovery, in order to understand factors that may affect movements and mixing. Yellowfin and skipjack were also analyzed for comparison, with most results for these species in the appendix. Secondly, we investigated the spatial patterns of tag recoveries in the catch, in order to determine whether the proportions of tags observed in the catch were likely to match those in the overall population, as the stock assessment assumes. Finally, we analyzed the effects on the stock assessment results of removing groups of tags. A related paper (Kolody & Hoyle 2013) applies statistical tests for incomplete mixing to the bigeye, yellowfin, and skipjack tunas within the spatial structure of the most recent assessments.

Methods

The tagging programs included in the analyses were those used in the stock assessments. These were the Pacific Tuna Tagging Programme (PTTP), and the Regional Tuna Tagging Programme (RTTP) (Table 1). The RTTP actually comprises several tagging programmes, including the Philippines Tuna Research Project (PH), the Kiribati in-country Tagging Project (KI), the Fiji in-country tagging project (FJ), and the Solomon Islands in-country tagging project (SB). Data for the Coral Sea Tagging programme were not included. The PTTP includes PTTP phase 1 in PNG and the Solomon Islands, PTTP phase 2 in the Central Pacific and Western Pacific, and the PNG Tuna Tagging Project. Tag seeding and purse seine-based tagging were excluded. PTTP Central Pacific tagging included some releases outside (to the east of) the WCPFC region, and these tags have been included in analyses.

During the PTTP, tag recovery dates and locations were validated by comparing recovery information against external information such as vessel monitoring system (VMS) and logsheet data. For recovery analyses of PTTP data, only validated tags with best_catchdate, best_lat, and best_lon assigned were used in most cases (Table 2). Where tags without an assigned best_catchdate were used, this is stated.

Displacement distance was the distance on the surface of the earth, calculated by measuring the chord between the release and recovery points. Time at liberty in days was calculated by subtracting the validated recovery date from the release date. Where times at liberty are reported in quarters, they are measured from the release date (0-91, 92-182 days etc) rather than based on fixed periods (i.e. released January-March, recovered April-June = 1 qtr at liberty). Mixing periods for tag data included in MULTIFAN-CL are based on fixed periods.

Displacement model

Observed displacement was plotted against time at liberty by species and region of release, and by tagging program, with data binned into groups by 100s of days at liberty.

Given the assumed mixing period of 2 quarters for bigeye and yellowfin and 1 quarter for skipjack assessments, we selected observed displacements with time at liberty of at least 2 quarters (183 days) for bigeye and yellowfin and 1 quarter (91 days) for skipjack. Observed displacements were plotted against longitude of release, with longitudes binned into 10 degree groups, the bin label representing the lower boundary. Median days at liberty were estimated by longitude group and plotted on the same figure.

Spatial patterns in observed displacements depend on many factors, including the distribution of releases, the distribution of fishing effort, selectivity of the fisheries and tag reporting rates. Size at release/recovery may contribute to observed displacement, given the selectivity of the various fisheries that capture tagged tuna, and possible ontogenetic changes in behaviour as the fish grow. Generalized additive modelling was used to investigate factors associated with the observed displacement. For all species and tagging programs the data included recoveries that had been at liberty for at least 1 quarter.

Models were developed in the statistical software R (R Core Team 2013), using the package "mgcv" (Wood 2006), which estimates effective degrees of freedom for smoothed variables using cross-validation. We fitted the following model to data by tagging program, for the PTTP tagging program and a grouped 'RTTP' dataset, and for bigeye, skipjack, and yellowfin. Analyses labelled RTTP included data from the Coral Sea, Fiji, Kiribati, Philippines, RTTP, and Solomon islands tagging programs, but results were similar when only the RTTP data were used. A log transformation was used in order to normalize the residuals.

$$\log(displacement) \sim s(days) + s(length_{rel}) + s(lat_{rel}, long_{rel})$$

Similar models were fitted to data collected in the eastern Pacific from tags released by the IATTC, but without the spatial effect since all tags were released within 2 degrees of longitude and 4 degrees of latitude.

We plotted the predicted displacement of fish from the model across the observed range of each parameter with the other parameters fixed, along with 95% confidence intervals for the first two variables. The fixed value for time at liberty was 1 year, release length was the mean of the observed lengths at release for the species and tagging program, and release location was 150°E and 0°N. The spatial effects are influenced by the behaviour of the fish at a location, but also and perhaps to a greater extent by the spatial distribution of the fishing effort that recovers and (importantly) reports tags. While this is a quantitative analysis, we use it more in the sense of a qualitative exploratory summary of some important factors.

Spatial Variation in Tag Density

The proportion of tagged fish in the catch can be used to indicate the spatial variation of tag density in the population. An adequately mixed population should show relatively consistent tag densities across most of the population. Although there will be some spatial variation (which is inevitable), the average tag density across the catch should match the average tag density across the population. To the extent that it is higher or lower, it will bias the fishing mortality higher or lower.

Tag density is estimated by combining tag recoveries with purse seine catch. We mapped the distributions of tag releases, purse seine catch by species and effort type (associated and unassociated) during and shortly after the RTTP and PTTP, and the density of tag recoveries (tags per unit of catch). The analysis was restricted to the purse seine fishery because we have the most confidence in the spatial and temporal consistency of the reporting rates for this fishery, the majority of reported tags come from this fishery, and the prior distribution assigned to the reporting rate of this fishery is influential in all tropical tuna assessments. Catch data to the west of 150W were obtained from the 8 July 2013 version of the SBEST database (Lawson 2012), while catch data to the east of 150W were obtained from the SDFWN database, provided by the IATTC. For the SSAP, pole and line catch was also included. Catches were summed over years, comprising 1977-1982 for the SSAP, 1990-92 for the RTTP, and 2007-12 for the PTTP. Only tags recovered after the mixing period (in days at liberty) were included. Although these can be influential, tag numbers were not adjusted for reporting rates or fishery selectivity. Selectivity varies between the associated and unassociated fisheries, but is assumed to be the same (for bigeye and yellowfin but not for skipjack) within each fishery across regions 3 and 4.

Catches are plotted on the nominal scale, and also on the log scale to reveal the trends in areas with less catch. This is helpful because inferences from tagging are based on ratios. Given the high density variation across the maps, tag recovery density plots were also reported on a log scale with contour lines at intervals of 1.5 log(tags/tonne). This implies that tag densities multiply by 4.6 with each contour line. We recognize that further disaggregation by size would be useful to minimize effects of spatial variability in fish size and gear selectivity.

Next, tag densities were modelled in the statistical software R (R Core Team 2013), using generalized additive models with the package "mgcv". We fitted the following model to data by tagging program, for the PTTP tagging program and a grouped 'RTTP' dataset, and for bigeye, skipjack, and yellowfin. Tag returns per 1 degree square were modelled as a function of catch and location, using a delta lognormal model.

The probability of observing tags was modelled with a binomial distribution as:
$tags > 0 \sim s(lat, long) + catch.$

The number of tags observed in nonzero cells was modelled assuming a lognormal distribution, as $\log\left(\frac{tag}{catch}\right) \sim s(lat, long)$, with cells weighted by catch.

Data were included for grid squares within the WCPO in which at least 30 tonnes of purse seine fishery catch were taken during the defined period. For the SSAP, pole and line catch was also included. The dimension of the basis used to represent the smooth term (k) was set to 100 for the delta component, and 50 for the lognormal component, except for yellowfin in the SSAP where it was set to 25 due to sparse data.

We plotted tag density as the expected number of tags returned per 1000 tonnes of fish, across all 1 degree squares with at least 30 tonnes of purse seine (and pole and line for the SSAP) fishery catch reported during the defined period. Tag density was colour coded, with contour intervals across the range 1 to 15 tags per 1000 tonnes. The purse seine fishery catch distribution was plotted over the top. While this provides a general indication of the variability in tag density, we recognize that there is a technical shortcut that could be misleading. Specifically, we present the tag density when tag and catch distributions are summed over time. It would be preferable to present the mean of the tag densities calculated from a series of discrete time windows (e.g. the ratio of sums will be different from the average of ratios). This has not yet been done due to a shortage of time, and the need to explicitly account for the implications of small sample sizes.

Bigeye and Yellowfin Assessment Implications of Alternative Tag Assumptions

We investigated how changing the tagging data affected recent bigeye and yellowfin assessment results. We reran the 2011 stock assessments after removing tags released in one region of the model at a time (regions shown in Figure 7), for regions 3, 4, and 5, and for more than one region at the same time. When dropping tags in each region, we identified all tag groups released in that region. For each tag group we replaced all the releases with a single tag released at a length of 30 cm (a data editing convenience that has minimal effect on the likelihood, and ensures that model structure is otherwise maintained), and removed all recoveries of that release group. Models were run using the version of MULTIFAN-CL applied during the bigeye review. Developments since that time have not significantly affected the way the tag data are modelled. We examined the reporting rate parameter estimates of the bigeye stock assessment with region 5 releases removed, to determine whether removing these tags also removed constraints on the biomass due to reporting rate estimates on the parameter estimation boundary.

We also investigated the effects of changing the assumptions about tags on the model results, by extending the mixing period from 2 quarters to 4 quarters. For bigeye we extended the mixing period for the reference case and for the model without region 3 and 5 release groups. For yellowfin we extended the mixing period for the reference case only.

Results

Tag recovery numbers by mixing period

We calculated the numbers of tags recaptured after a range of mixing periods, based on days at liberty (Table 3). Numbers dropped away rapidly in most cases. For bigeye the number of recoveries after a mixing period of 2 quarters (compared to the MULTIFAN-CL mixing period of 3-6 months, depending on release date) was low in region 3 at 11% in the RTTP and 17% in the PTTP, but higher in region 4 (59% RTTP, 25% PTTP), region 5 (78% RTTP) and for EPO releases (84% PTTP). After a mixing period of 1 year tag recovery numbers were low in region 3 (3% RTTP, 4% PTTP), higher in region 4 (28% RTTP, 6% PTTP), region 5 (68% RTTP) and the EPO (33%).

For skipjack, returns were high after 1 quarter of mixing in region 3 where the majority of recoveries occurred (33% RTTP, 30% PTTP). By 4 quarters numbers were somewhat lower (6% RTTP, 3% PTTP) and had dropped below 1% by 7 quarters. For yellowfin in region 3, returns were moderate with 21% (RTTP) and 19% (PTTP) occurring after a 2 quarter mixing period. After 4 quarters the numbers were down to 8% (RTTP) and 7% (PTTP) and dropped below 1% by 9 quarters after release.

Displacement analyses

Comparisons of observed bigeye displacements by time at liberty and by region suggested that in both the RTTP and the PTTP, observed displacements (which are driven by effort distributions and fishery selectivity as well as fish behaviour) were largest on average for tags released in region 4 and smaller for region 3 (Figure 7). There were relatively few releases in region 5 during the PTTP, but for the RTTP the region 5 releases had the smallest observed displacements of any region. Yellowfin observed displacements by time at liberty and region for the RTTP were largest on average for region 4 releases. However, observed displacements for tags released in regions 3 and 5 were similar to one another. During the PTTP the observed displacements for tags released in region 5 were similar to those for region 4, while observed displacements were consistently smallest for tags released in region 3.

Observed displacements for bigeye, yellowfin and skipjack after at least 2 quarters at liberty (1 quarter for skipjack) (Figure 8) suggested strong spatial variation within region 3, with the smallest displacements for fish released in the far west of region 3 (Indonesia and the Philippines), and also in the area from 135E to 155 E (Papua New Guinea to the Solomon Islands). Similar spatial patterns were observed for all three species, though sample sizes were small for bigeye in region 3. In contrast, median times at liberty appeared relatively consistent across most longitudes.

Modelling effects on observed displacements using gams indicated that all parameters investigated affected observed displacements for times at liberty > 91 days. All effects were statistically significant (generally $p << 0.01$) and we did not observe problematic patterns in residuals after log transformation of the data. We note however that interactions were not explored and may be expected among some variables.

Time at liberty had a nonlinear relationship with observed displacement (Figure 9). Observed displacements for bigeye in the PTTP increased to about 9 months at liberty, declined to 18 months and subsequently increased again. A different pattern was observed for bigeye in the RTTP with a decrease in observed displacement with time to about 1 year at liberty, followed by an increase to about 2 years at liberty and little change after that. For EPO releases of bigeye by the IATTC, displacements increased until 6 months at liberty before decreasing to a low point after a year at liberty and increasing again (not shown).

Greater length at release was associated with smaller displacement for bigeye to a length of about 80 cm, for both the RTTP and PTTP tagging programmes (Figure 10). Given that small bigeye tend to be vulnerable to the FAD purse seine fishery for longer than larger bigeye there is potential for parameter correlation in the analysis, so we reran the PTTP analysis with recoveries grouped by days at liberty. (Sample sizes were too small to do the same for the RTTP). These analyses also showed a negative relationship between size at release and displacement distance over a size range from 40 to 80cm, apart from releases recovered after more than one year, for which the relationship was also negative but not statistically significant (Figure 11). Similarly, for release by the IATTC in the EPO, expected displacement decreased up to a length at release of about 75 cm.

We plotted predicted displacements for fish of median length after one year at liberty (Figure 12). We observed spatial patterns in observed displacement, as expected given the spatial variation in fishing pressure and potential variation in reporting rates among fleets. During the RTTP, expected displacements after 1 year were at a minimum and therefore quite small, but greater displacement was apparent further east, further from the main areas of purse seine catch. For the PTTP analyses the predicted displacements were at a maximum after 1 year at liberty and therefore larger than RTTP, with median displacement close to 500 km for releases in the Bismarck Sea and Solomon Sea, and from less than 1000 up to 2000 km in region 4. Displacements were also small in the far western Indonesia-Philippines area.

It is useful to compare these displacements to other species for which there are more data. Skipjack and yellowfin tuna also had smaller median displacements for releases in the Bismarck and Solomon seas, for both tagging programmes, in the neighbourhood of 500 km after 1 year at liberty for a fish of median size. Displacements were also small in the far western Indonesia-Philippines area. Observed displacements were smaller in the Indonesia-Philippines area for all three species, and also in the Bismarck Sea - Solomon Islands area.

Spatial Variation in Tag Density

Tag release densities were quite aggregated, with the most releases by species in a single 1 degree cell representing 7.5% of all releases for skipjack, 8.3% for skipjack, and 17.3% for bigeye (Figure 14). The largest bigeye releases occurred in the central Pacific, with 7068 tags released in association with the 0N, 170W Tao buoy. The largest yellowfin and skipjack releases occurred in the Bismarck Sea and Solomon islands.

Purse seine catch distributions were also heterogeneous, with higher catches of all species in the western Pacific, north of Papua New Guinea and the Solomon Islands (Figure 15 and Figure 16). The spatial distributions of associated and unassociated catch overlapped substantially, but unassociated catch tended to extend further north and east.

Tag recovery densities for bigeye were more patchy than the other species, partly due to the comparatively low number of tags released (Figure 17). Tag returns per tonne of catch showed considerable spatial variability at both 1 degree (Figure 17) and 5 degree (Figure 18) square resolutions. The densest areas of bigeye recovery occurred in the central Pacific close to the locations of the largest tag releases, but estimates are less reliable for this area due to less precise catch information. The areas of highest purse seine catch (within the white contour lines on the plot) did not in general overlap the areas with highest densities of returned tags. The relationship between the average tag densities across the catches and the average densities in the population have not been estimated, since the distribution of the population is unknown.

A generalized additive model of tag density distribution in general fitted the data reasonably well for skipjack and yellowfin (see appendix), with good relationships between theoretical quantiles and residuals, but fitted bigeye worse than other species due to the more limited dataset.

Assessment Implications of Alternative Tag Assumptions

We investigated conflicting information in the model by comparing the influence of different parts of the data. In particular we investigated the effects of the tag releases in each region by dropping all tag releases in each region, and for combinations of regions. For bigeye tuna, removing region 3 or 4 releases resulted in little change in biomass relative to the reference case across the whole time series (Figure 19), while removing region 5 releases resulted in approximately double the reference case biomass across all regions. Removing both regions 3 and 4 only slightly changed the total biomass. Removing regions 3 and 5 together increased the biomass substantially across all regions, but by less than removing only the region 5 releases. Removing region 4 and 5 tag releases together dramatically increased the total biomass by almost an order of magnitude. Progressively removing tag releases from region 5, region 4, and region 3 resulted in stepwise increases in biomass estimates to a very high level, suggesting that at the lower biomass the model was fitting worse to other parts of the data (likelihood components at the higher biomass and without tags indicated better fit to length data (192 likelihood units), effort deviates (84) and weight data (18), and worse fit to the catch data (70)). Extending the mixing period from 2 quarters to 4 quarters slightly increased the biomass, both for the reference case and for the model with only region 4 tag releases. In each case the biomass changes were largely shared across all regions, since relative biomasses are linked via shared longline catchability.

Removing the region 5 releases from the bigeye assessment changed a number of the reporting rate (RR) estimates (Figure 20). The RR estimates associated with the region 5 Australian longline fishery (CS_rel_LL_R5_AU recov) were no longer on the boundary at 0.9. However, the increased biomass estimate in this model run was associated with higher reporting rate estimates in many cases, as can be seen in the figure where the black dots are in most cases above the red triangles. After these increases, four reporting rate estimates were now at the boundary in this model, for tags released in the RTTP (region 3 pole and line fisheries and the region 3 Philippines Indonesia purse seine fishery) and the PTTP (region 4 purse seine fishery and region 1 Japanese purse seine fishery). The reporting rate for RTTP releases in the region 4 purse seine fishery was also well outside the prior which suggests that some inconsistency in the model structure remains.

Comparisons of the observed and expected releases for these tag program – fishery combinations indicated quite low recapture numbers in most cases, which would make little likelihood contribution and so would have only small effects on biomass estimates. However, several large mismatches occurred in the region 4 purse seine fishery recoveries of PTTP releases. Note that the tag fit diagnostics only reveal part of the problem. MULTIFAN-CL estimates errors around all parameters, and a poor fit to the tag data is usually improved somewhat by changing other parameter estimates in a predictable way (e.g. if predicted tags are greater than observed tags for a particular recovery event, then the corresponding predicted catch will likely be less than the observed catch, and of a magnitude that depends on the catch error variance assumption and number of tag recoveries).

Discussion

This paper documents three main lines of work. Firstly, we examined fish displacements between release and recapture, to explore some of the factors involved in the interaction between fish movement and the chance of tag recovery at the fish's location. We found that displacement varied significantly with time at liberty, release size, and release location. Cyclic movements and smaller movements for larger bigeye were suggested, but the nature of displacement data makes it difficult to draw firm conclusions. Such features would likely be significant for the stock assessment and should be investigated further with other datasets, and via simulation. Secondly, we investigated spatial variation of the density of tags in the catch, in order to identify how well the assumption of equal vulnerability of tagged and untagged fish was being met. We found strong gradients in tag density with peaks at locations where releases had occurred. The variation was large for all species, particularly in region 3. In region 4, where bigeye releases were more widely dispersed, densities were also more widely dispersed, but still varied spatially with large peaks near large releases. Simulation will be needed to help interpret how the proportions of tags in the catch might relate to the proportions of tags in the population. Finally, we investigated the influence of the tagging data on the stock assessment. We found that biomass across all regions was constrained by poorly fitting tag data and model misspecification in region 5, and after removing these relatively few tags the biomass estimate doubled. We suggest that both the tag and the non-tag parts of the assessment should be very thoroughly evaluated and potentially reconfigured. We also advise that the information in the tagging data should be further evaluated before including it in the stock assessment.

Further discussion is provided below, with a summary of recommendations for the stock assessment. However, please note that we are still digesting the implications of these findings. This should be interpreted in the spirit of a progress report rather than the definitive analysis.

Information from displacements about fish movement and tag recovery

Our analyses of observed displacements by species suggested much variability among species and areas. For example, displacements were generally largest for fish released in region 4 (Figure 7, Figure 12). Larger bigeye appear to be recaptured at smaller distances than smaller fish according to both the RTTP and PTTP analyses, and in analyses of IATTC releases, and this relationship was consistent no matter how long the time between tag and recapture. Bigeye tagged at smaller sizes may therefore be likely to mix more rapidly than larger fish within the large regions of the WCPO bigeye assessment. Some form of residential behaviour may occur for larger fish. If this is the case, it may be appropriate to adopt a size limit for including bigeye in the newly tagged population. Alternatively, the very long term recaptures in Figure 6 may result from bigeye that were tagged at spawning sites returning to those sites, and these adults may be vulnerable to being caught in this one location by a fleet that consistently reports tags. Cyclic behaviour has been observed for large bigeye based on archival tag data (Evans, Langley, Clear, Williams, Patterson, Sibert, Hampton, & Gunn 2008), suggesting the possibility of seasonal migration (Hampton & Gunn 1998). However, the observation may also be affected by the selectivity of the fisheries, given that most reported bigeye recaptures come from FAD fisheries, which take small bigeye. *The observation of size-dependent displacement rates should be followed up with independent datasets, such as analyses of horizontal movement data from archival tags to determine if such size effects are present. Simulations should be used to investigate possible effects of age-dependent movement and cyclic behaviour on the stock assessment.*

Observed displacements also varied among and within regions, but these results must also be viewed thoughtfully. These observations are affected by fish movements, but also by fishing effort distributions, selectivity, reporting rates, and errors in reported locations and dates. Tuna may genuinely move more freely in the open ocean, further from land masses, but effort and catch are generally higher near the region 3 tag release areas than in region 4, which might cause a similar result even if displacements were identical. There were also strong spatial patterns in observed displacements within region 3, even considering only those fish at liberty for more than the currently assumed mixing period (Figure 8, Figure 12). The two areas with the smallest observed displacements for all three species were Indonesia-Philippines area in the west of region 3, and the Bismarck Sea – Solomon sea area in the south of region 3. These are also areas with high numbers of releases and relatively high catch, but the median times at liberty in these areas showed no tendency to be shorter than elsewhere.

Validity of assumptions about tag distribution in the population

A fundamental assumption in tag modelling is that proportions of tagged fish are the same in the catch as in the relevant proportion of the population. This is usually assumed to occur because the tags are mixed through the population (via the efforts of the taggers and/or the movements of the fish). It could also occur because fishing in areas of higher tag density balances fishing in areas of lower tag density, which would result in an unbiased F estimate. However, there will always be uncertainty about whether this has occurred, given the uncertainty in the distributions of catch, population at age/size, and tag density.

Tags have been both distributed (Figure 14) and recovered (Figure 17) across a broad range of locations, particularly in region 4. We have compared tag recovery distributions after the currently assumed mixing period with the catch (tags per tonne by 1 degree square accumulated over the whole tagging programme), but this comparison is difficult for bigeye for several reasons. First, a reasonably high proportion of tag recoveries have not been validated, and the rate of validation varies through time and spatially. Second, the tag densities have not been adjusted for the reporting rates of the different components of the fleet, nor for possible variation in validation rates in space. Third, they do not take into account the selectivity of the fisheries, which differs between associated and unassociated sets, though this may be less significant for bigeye than other species since the great majority of the catch comes from associated sets. Fourth, the catch estimates for bigeye are based on estimates of species composition in the total catch, and contain considerable uncertainty particularly in region 4 due to lower levels of spill sampling; uncertainties that may include spatial trends. We therefore cannot determine whether or not adequate mixing has been achieved, particularly in region 4. The patterns of tag density in region 3 are clearer given the larger numbers of tag returns and the higher, better-estimated bigeye catches. Tags appear to be somewhat aggregated in the Bismarck Sea – Solomon area. Similar patterns are observed in the yellowfin and skipjack tag density data. *Additional analyses should be carried out to take into account variation in fish sizes and reporting rates, and uncertainty in catch.*

We may also consider whether catches with higher tag densities may balance those in areas with lower tag densities, so that the proportions of tagged fish (of the appropriate size) match the relevant proportions in the overall population. We have no *a priori* reason to expect that this would be the case, but given that incomplete mixing exists, the nature of the mismatch will determine if F is over-estimated, under-estimated or coincidentally unbiased. It is difficult to be sure without knowing the distribution of the population or how it has changed through time. *Simulation would be helpful to explore this issue, and investigate the level of uncertainty given the incomplete mixing.*

Sensitivity of the model to removal of tag subsets

Removing regional subsets of tag releases from the bigeye (and yellowfin – see appendix) stock assessment substantially affected the population dynamics. The assessment was particularly affected by the initial removal of region 5 tags, due to the removal of the constraint associated with the Australian longline fishery's RTTP reporting rate parameter on the 0.9 boundary, as described earlier. After removing the R5 tags, the assessment appeared to be constrained by the region 4 purse seine fisheries' PTTP reporting rate, which was now at the 0.9 boundary (Figure 20). Sequentially removing the R4 and then R3 tags removed all parameter boundary constraints (but also the useful information in the tagging data) and resulted in further large changes in the population dynamics. The bigeye stock assessment biomass scaling appears to be largely determined by tagging data associated with reporting rate parameters on the 0.9 boundary, such that more (and sometimes far more) tags are observed than predicted.

The effects of these poorly fitting release groups in one region are distributed across all regions by the shared longline catchability assumption. This assumption is designed to constrain the model into a reasonable parameter space, and to keep biomass estimates in different regions at reasonable levels (as determined by relative catch rates in longline fisheries). However, it also gives assumptions in one region of the model the power to affect all the other regions.

The problematic tag fits each had particular characteristics. The displacement (Figure 7) rates of the region 5 tags appear different from tags in the rest of the model, with many were recaptured very close to their release location, and after unusually long times at liberty (Table 3). The model is set up with the simplifying assumption that fish on average move in similar ways, and currently the model assumes no age-dependence in movement, so groups of fish such as those in region 5 (which appear to have different characteristics) are difficult for the model to fit. The region 4 tags on the other hand may have been behaving as expected, but catch estimates for region 4 were uncertain during the 2011 assessment, and the largest differences between observed and expected tags are associated with unusually low R4 catch estimates. It appears likely that these individual catch estimates were underestimates. The model is currently parameterized to assume that the region 4 purse seine catch has low error. More recent updates to purse seine catch estimates have improved the situation (Lawson 2013), but uncertainty in bigeye purse seine catches remains (particularly in some periods and areas), given that it is not observed directly but estimated from observer grab samples of species composition that are subsequently adjusted for bias.

The high levels of biomass estimated without the tagging data were over 20 times the current estimates, with minimal fishing mortality. Ideally, the information in the tagging data and in the other components of the model would be providing similar information about biomass. Both aspects of the model require further investigation. Tagging programmes can potentially be more informative about absolute abundance than other data in the stock assessment, but this requires that the tag dynamics assumptions are valid.

Extending the mixing period from 2 quarters to 4 quarters had relatively little effect on the biomass estimates in the bigeye model. On one level this result is consistent with the gam analyses of displacements, which suggest that mixing for bigeye tuna may reach a limit with time. However, a better explanation of this insensitivity to the mixing rate lies in the region 5 tags and the fishery 11 (Australian longline fishery) reporting rate. Even after 4 quarters many more tags are observed than expected (i.e. more than 50% of these tags were recovered after more than 10 quarters), and the RR parameter continues to place a ceiling on the biomass estimate. If bigeye mixing does reach a limit with time, then simply extending the mixing period will not resolve the problems with the tag mixing assumption.

Bigeye assessment recommendations

Addressing the bigeye review recommendations for the bigeye stock assessment will require changes to the way the tagging data and other data components, such as the size and CPUE data, are modelled.

The first priority must be to *focus on the structure of the model aside from the tagging data*. The model without tagging data estimates very high biomass, which indicates that the other data components are pulling the model in a different direction from the tagging data. These parts of the model should be examined carefully to understand when and why they fit the data and are not in conflict either with one another or with the tagging data. Conflicting information in different components of the data can substantially affect biomass estimates. As part of this process we will address recommendations from the bigeye review with respect to modelling size and CPUE data. In addition, previous work examining model sensitivities (e.g. Harley et al. 2010;Hoyle, Langley, & Hampton 2008) has been affected by the biomass ceiling imposed by the region 5 tagging data, and the conclusions of this work must be reconsidered by rerunning the analyses with tagging data removed. Repeating relevant parts of this work, with appropriate modifications and additions, offers an accessible start to work towards a better model.

The next priority is to identify how to model the tagging data, extracting the useful information without introducing unacceptable bias. We suggest that the region 4 tags are most likely to conform to standard tag modelling assumptions and hence may be more informative within the model. Given the large number of tags they are potentially influential, and if they mix more rapidly in the open ocean than tagged fish in other areas, it will be easier to model them appropriately. Further work needs to be done to investigate the distribution of the tags in comparison with the catch, in particular exploring alternative estimates of bigeye catch and catch distribution, and comparing tags and catch at larger spatial scales, such as 5x5 rather than 1x1. Analyses should also consider the reporting rates and size distributions of the fisheries that take the catch, using for example the SVTD method (Kolody and Hoyle submitted). Many tags released in region 4 are recovered further east, outside the WCPFC commission area, and we need to carefully consider how to model them. Excluding them from the model would be problematic because the model does not account for trans-border migration. Similarly, including them in the model is problematic because it requires the catch in the EPO to be considered. It may be appropriate to include the tags and the EPO catch in a separate fishery. Simulation may help to identify the best way forward.

Changes to the spatial structure (and potentially sub-stock structure) may be required. Further exploration will be required to identify spatial sub-regions within which adequate mixing can be assumed, and the length of time required for mixing to be sufficient. Modelling the tags in region 4 may require dividing the region into 2 or more sub-regions by longitude, to improve the chances that tags are mixing after an appropriately chosen time at liberty. However, defining additional regions requires estimating considerably more parameters, so should be undertaken carefully. Alternatively it may be possible to define separate fisheries within the existing region 4, and allow each fishery a separate reporting rate, to allow for any existing spatial variation in tag densities. Testing the alternatives requires simulation as a high priority, given uncertainties about the distribution of tags within the population. However, simulating the complex dynamics will not be straightforward, and may require adaptation/application of SEAPODYM or a similar model.

Modelling the region 3 and region 5 tags may be more difficult given the potentially different behaviour and the complex geography. Many region 5 releases are recaptured close to their release point (Figure 6 and Figure 7), and bigeye may displace less as they grow larger. There are relatively few region 5 tags with 363 recoveries from 5000 releases, and they should not be given undue weight in the assessment. It may be difficult to design a new regional structure that would allow them to mix adequately. Region 3 releases are also relatively limited, with only 6840 PTTP releases and 1100 validated recoveries, compared with 27000 and 6400 from region 4.

If the slower mixing of large fish is confirmed, it would be helpful to define an upper limit for the size of releases to include in the model, and may also be useful to assume age-dependent movement. *Another useful step would be to reduce the catch deviate penalty in the two region 4 PS fisheries well below 100000.* Though recent updates have improved the situation (Lawson 2013), bigeye purse seine catch in some areas and periods remains uncertain, and if catch is underestimated then the low number of predicted tags can affect the likelihood. A lower penalty would allow the model to fit the tags by increasing the estimated catch for that quarter, rather than lowering the overall biomass estimate. Information in the tag data is conditional on knowing both the tag numbers and the catch, and uncertainty in both must be taken into account.

The model is using the reporting rate parameter to account for differences between observed and expected tag returns. This represents not only the effects of the reporting rate, but multiple factors including differences between the proportions of tags in the catch and in the relevant portion of the population, and errors in the catch estimates. *We should therefore avoid tightly constraining the reporting rate with strong priors, unless confident that the other assumptions are being met. The prior distributions on the reporting rates, which are currently estimated by analysing tag seeding data (Hoyle 2011), should be reconsidered to take into account uncertainty in the tag distribution, and any uncertainty in the associated catches not included in the catch likelihood, as well as in the reporting rates themselves. Perhaps an even better way to model the uncertainty in the fit to the tagging data would be to change MULTIFAN-CL so that the user can adjust the weight on the tag likelihood so that it reflects the amount of information in the data.* In addition, when differences between observed and expected tag returns are too large for the model to raise the reporting rate high enough to explain the observations, the reporting rate parameter boundary effectively puts a ceiling on the population size estimate. *Parameters estimated against boundaries are a warning sign in any estimation model, and should be investigated carefully in future assessments.*

Finally, if we do not use tag recoveries to inform estimates of fishing mortality and biomass, tag movement data can still be used to inform movement rates through the use of a tag likelihood conditional on tag recapture rather than on catch. This approach has recently been used to include tagging data in SEAPODYM (Lehodey 2004). The approach has been previously explored as an option in MUTLIFAN-CL, and may be applied after further testing.

Acknowledgments

Thanks to the Western and Central Pacific Fisheries Commission for funding these analyses. Western and Central Pacific tagging was supported by the National Fisheries Authority of Papua New Guinea, the New Zealand Agency for International Development (PNG Tuna Tagging Project and Pacific Tuna Tagging Project Phase 2), the Australian Centre for International Agricultural Research, the 9th (SciFish project) and 10th (SciCoFish project) European Development Fund, Global Environment Facility (Pacific Islands Oceanic Fisheries Management project), the Republic of Korea, Republique Francais (Fonds Pacifique), Republic of China, Heinz Australia, and the University of Hawaii (Pelagic Fisheries Research Program). Thanks to Kurt Schaefer and the Inter-American Tropical Tuna Commission for allowing us to analyze their tagging data.

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Tables

Table 1: Releases and recoveries by tagging programme and bigeye stock assessment region.

Programme	Species	Region	released	recovered	With catch date	Validated date
RTTP	Bigeye	3	2590	560		
		4	1483	144		
		5	4490	380		
		6	4	1		
	Skipjack	3	70457	10518		
		4	12024	852		
		5	13276	813		
		6	5198	514		
	Yellowfin	3	32649	4528		
		4	3016	229		
		5	4732	341		
		6	1173	46		
PTTP	Bigeye	3	6839	1459	1433	1105
		4	26927	6384	5720	3183
		5	48	7	7	7
		7	6952	2370	2145	376
	Skipjack	3	224707	35595	34866	25490
		4	12895	1639	1609	1335
		5	8869	525	520	422
		7	53	3	2	25490
	Yellowfin	3	96006	14560	14450	11162
		4	4018	554	524	379
		5	5709	568	562	495
		7	336	78	70	16

Table 2: Releases and recoveries by species, release region, and year, including percentages of recoveries with validated dates and locations.

Species	Release_region	Year	Releases	Recoveries	Date reported	Validated_date	Validated_location
B	3	2006	562	229	100%	96%	96%
B	3	2007	268	26	100%	58%	50%
B	3	2008	1879	424	100%	65%	62%
B	3	2009	1204	342	97%	86%	80%
B	3	2011	354	56	98%	77%	75%
B	3	2012	2008	382	96%	68%	68%
B	3	2013	564	0			
B	4	2008	1736	570	99%	4%	4%
B	4	2009	6688	1445	90%	34%	32%
B	4	2010	8374	2304	91%	62%	53%
B	4	2011	4115	868	66%	23%	22%
B	4	2012	6014	1197	99%	87%	87%
B	5	2008	2	0			
B	5	2009	45	7	100%	100%	100%
B	5	2011	1	0			
B	EPO	2009	3051	1207	90%	30%	27%
B	EPO	2011	3901	1163	91%	1%	1%
S	3	2006	13947	2638	100%	93%	93%
S	3	2007	33942	4468	100%	76%	75%
S	3	2008	51742	8070	100%	65%	65%
S	3	2009	46186	9312	99%	86%	83%
S	3	2011	27183	5320	97%	75%	73%
S	3	2012	28311	5779	93%	41%	40%
S	3	2013	23396	8	100%	88%	88%
S	4	2008	57	4	100%	0%	0%
S	4	2009	12731	1627	98%	82%	75%
S	4	2010	47	8	75%	75%	75%
S	4	2011	40	0			
S	4	2012	20	0			
S	5	2008	1119	43	100%	60%	56%
S	5	2009	6205	340	99%	87%	81%
S	5	2011	1545	142	99%	70%	69%
S	EPO	2009	39	2	50%	0%	0%
S	EPO	2011	14	1	100%	0%	0%
Y	3	2006	7806	1805	100%	93%	93%
Y	3	2007	16409	2491	100%	80%	80%
Y	3	2008	31700	4452	100%	69%	68%
Y	3	2009	13286	2823	99%	86%	83%
Y	3	2011	11238	2203	98%	79%	77%
Y	3	2012	9607	785	95%	34%	33%
Y	3	2013	5960	1	100%	100%	100%
Y	4	2008	116	25	100%	12%	12%
Y	4	2009	3176	425	95%	72%	64%
Y	4	2010	348	55	96%	75%	71%
Y	4	2011	238	26	73%	23%	23%
Y	4	2012	140	23	100%	100%	100%

Table 3: Table showing the percentages of tags recovered following the specified mixing period, for mixing periods ranging from 0 to 12 quarters. Note that each row aggregates all recoveries during the current quarter and all later quarters, and the first row contains numbers rather than percentages, so for example, 537 bigeye *in total* were recovered from region 3 RTTP releases. Figures are shown for the RTTP and the PTTP, for regions 3 to 5, and for tags released during the PTTP to the east of the WCPO boundary. Only validated tags are included for the PTTP.

		RTTP			PTTP			
	Mix pd of N qtrs at liberty	Region 3	Region 4	Region 5	Region 3	Region 4	Region 5	EPO
Bigeye	0	537	132	364	1104	3183	7	376
	1	17.5%	78.0%	79.1%	32.1%	45.5%	100.0%	90.4%
	2	10.6%	59.8%	78.0%	17.3%	24.7%	100.0%	83.8%
	3	4.7%	46.2%	72.8%	9.3%	11.0%	57.1%	62.0%
	4	2.8%	28.0%	67.6%	4.3%	6.3%	28.6%	33.2%
	5	0.9%	18.9%	65.1%	2.4%	3.4%	14.3%	15.7%
	6	0.6%	12.1%	64.0%	1.7%	1.8%	14.3%	4.0%
	7	0.6%	9.1%	57.1%	1.3%	1.0%	14.3%	0.3%
	8	0.4%	6.8%	55.8%	1.0%	0.4%	14.3%	0.0%
	9	0.2%	6.1%	55.5%	0.9%	0.3%	0.0%	0.0%
	10	0.0%	5.3%	53.3%	0.8%	0.1%	0.0%	0.0%
	11	0.0%	3.8%	44.5%	0.5%	0.1%	0.0%	0.0%
	12	0.0%	3.8%	38.5%	0.4%	0.1%	0.0%	0.0%
Skipjack	0	9638	783	739	25425	1335	421	
	1	32.5%	62.8%	58.5%	30.0%	56.6%	78.9%	
	2	16.3%	47.9%	43.3%	12.6%	21.1%	51.1%	
	3	9.7%	32.7%	29.8%	5.6%	9.7%	22.1%	
	4	5.8%	16.2%	15.3%	3.0%	5.5%	10.5%	
	5	3.3%	9.1%	11.0%	1.8%	2.6%	5.0%	
	6	1.5%	2.8%	6.8%	1.1%	1.0%	4.0%	
	7	0.8%	0.8%	4.2%	0.7%	0.7%	1.9%	
	8	0.5%	0.5%	1.5%	0.5%	0.4%	0.5%	
	9	0.4%	0.0%	1.1%	0.4%	0.2%	0.5%	
	10	0.2%	0.0%	0.5%	0.3%	0.1%	0.5%	
	11	0.2%	0.0%	0.1%	0.2%	0.0%	0.0%	
	12	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	
Yellowfin	0	4079	202	325	11151	379	494	16
	1	33.8%	78.2%	40.0%	37.9%	62.5%	96.4%	68.8%
	2	20.5%	48.5%	34.2%	18.8%	41.7%	81.6%	50.0%
	3	13.6%	27.7%	24.3%	11.4%	23.5%	53.4%	18.8%
	4	8.4%	16.3%	18.5%	7.0%	14.2%	27.5%	6.3%
	5	5.1%	10.9%	16.3%	4.3%	10.0%	17.0%	6.3%
	6	2.6%	6.4%	11.4%	3.0%	7.9%	11.9%	6.3%
	7	1.6%	4.5%	8.9%	2.0%	5.8%	6.5%	0.0%
	8	1.0%	4.5%	7.4%	1.2%	4.2%	3.8%	0.0%
	9	0.6%	3.0%	6.5%	0.9%	3.2%	2.0%	0.0%
	10	0.4%	2.5%	5.8%	0.6%	3.2%	1.6%	0.0%
	11	0.3%	2.0%	4.6%	0.4%	1.1%	0.2%	0.0%
	12	0.2%	1.0%	3.4%	0.3%	0.5%	0.0%	0.0%

Figures

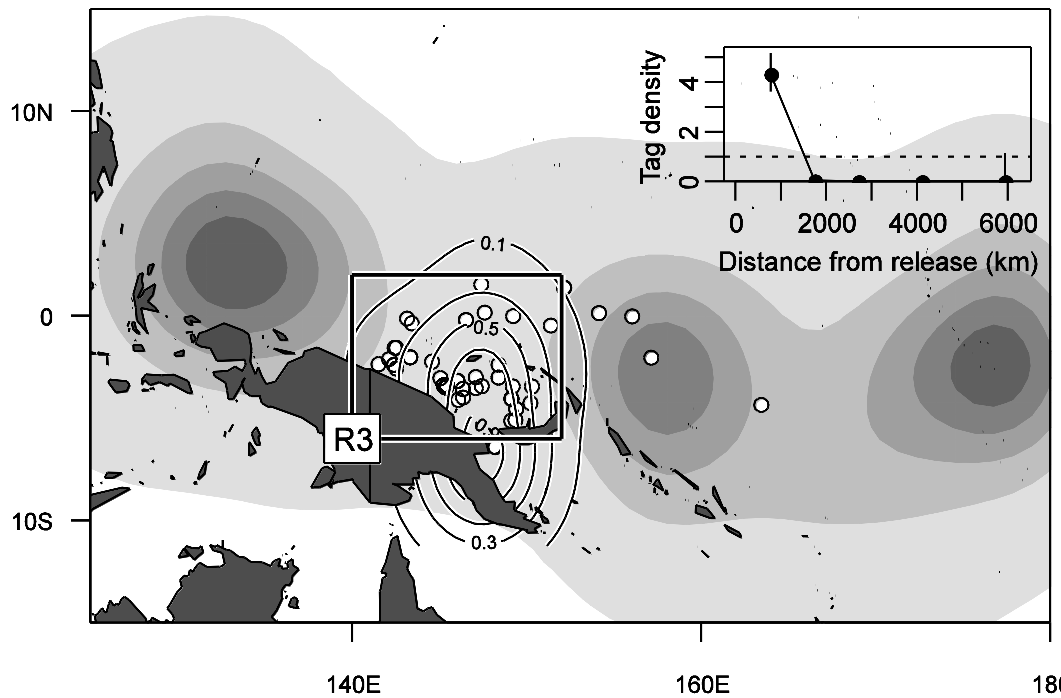


Figure 1: Map of skipjack catch, tag recoveries, and inferred tag density. Tags released in area R3 were recaptured in the marked positions 1 quarter after release. Density of tags per unit of catch is shown in the contour lines. The distribution of the catch in that fishery is shaded.

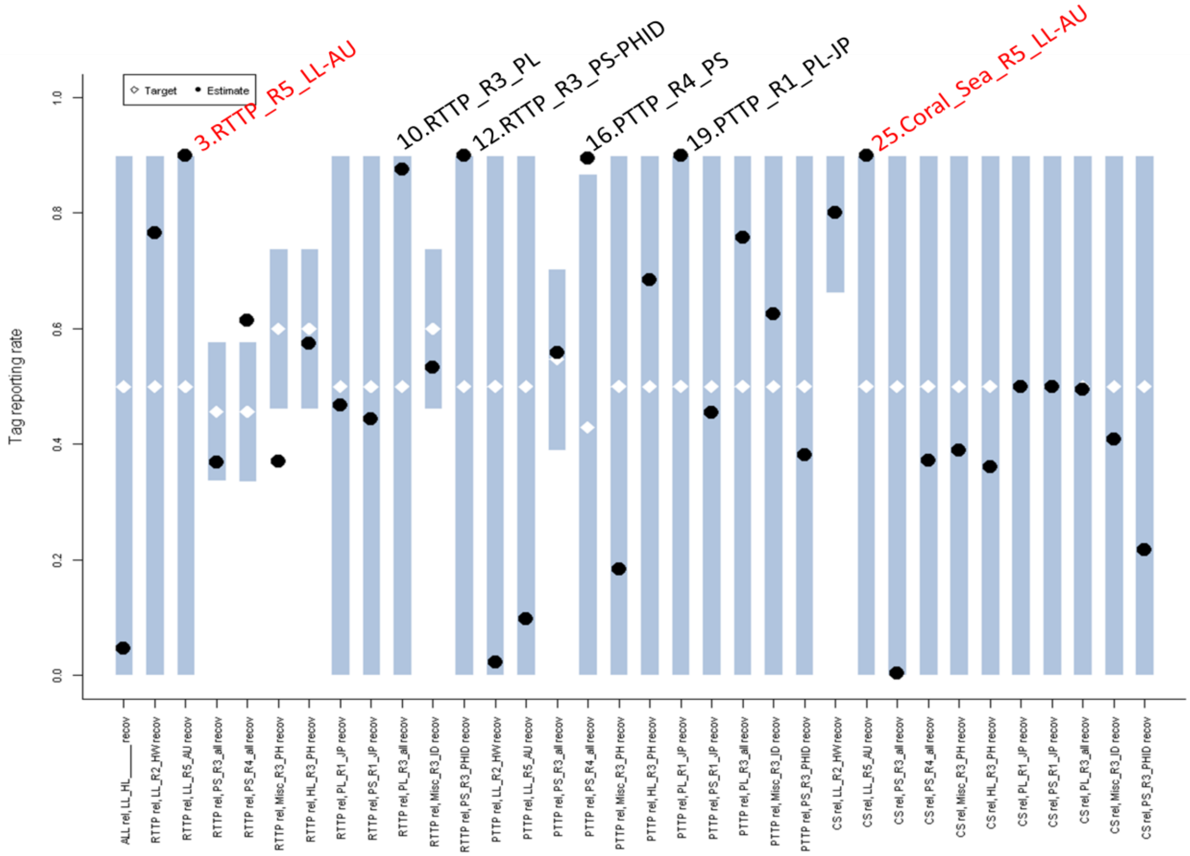


Figure 2: Estimated reporting rates for Run3j – Ref.case specific to each release program (RTTP, PTTP and CS) and recapture fishery group (histograms). Certain estimates are grouped over release programs and over recapture fisheries, (e.g. LL-ALL and HL fisheries: ALL rel.LL_HL_recov). The prior mean ±1.96 SD is also shown for each fishery.

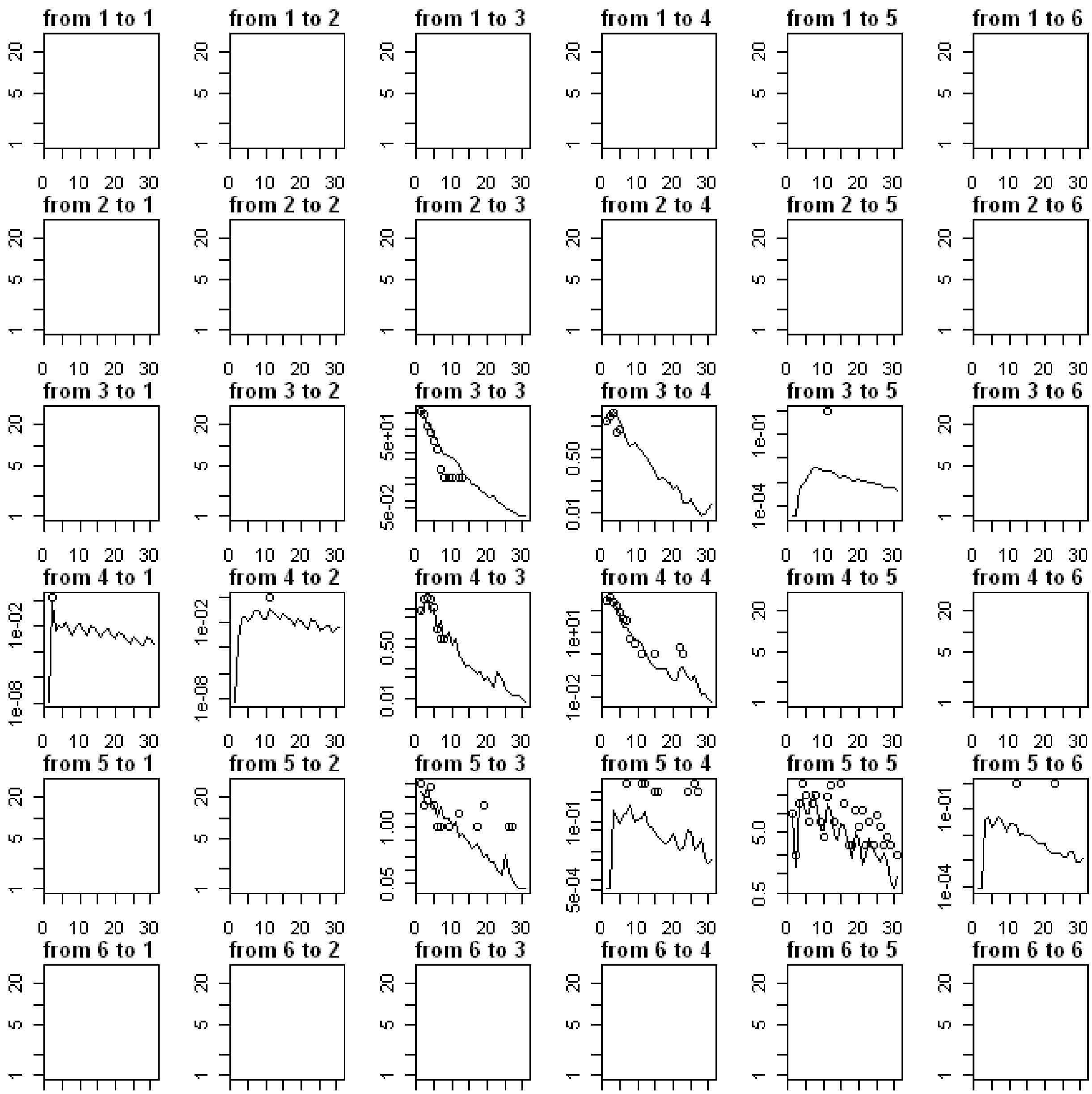


Figure 3: Predicted (lines) and observed (circles) recaptures of tagged fish by time period at liberty (quarter) from the region of release to the region of recapture. Y-axis represents (log-scale) recaptures.

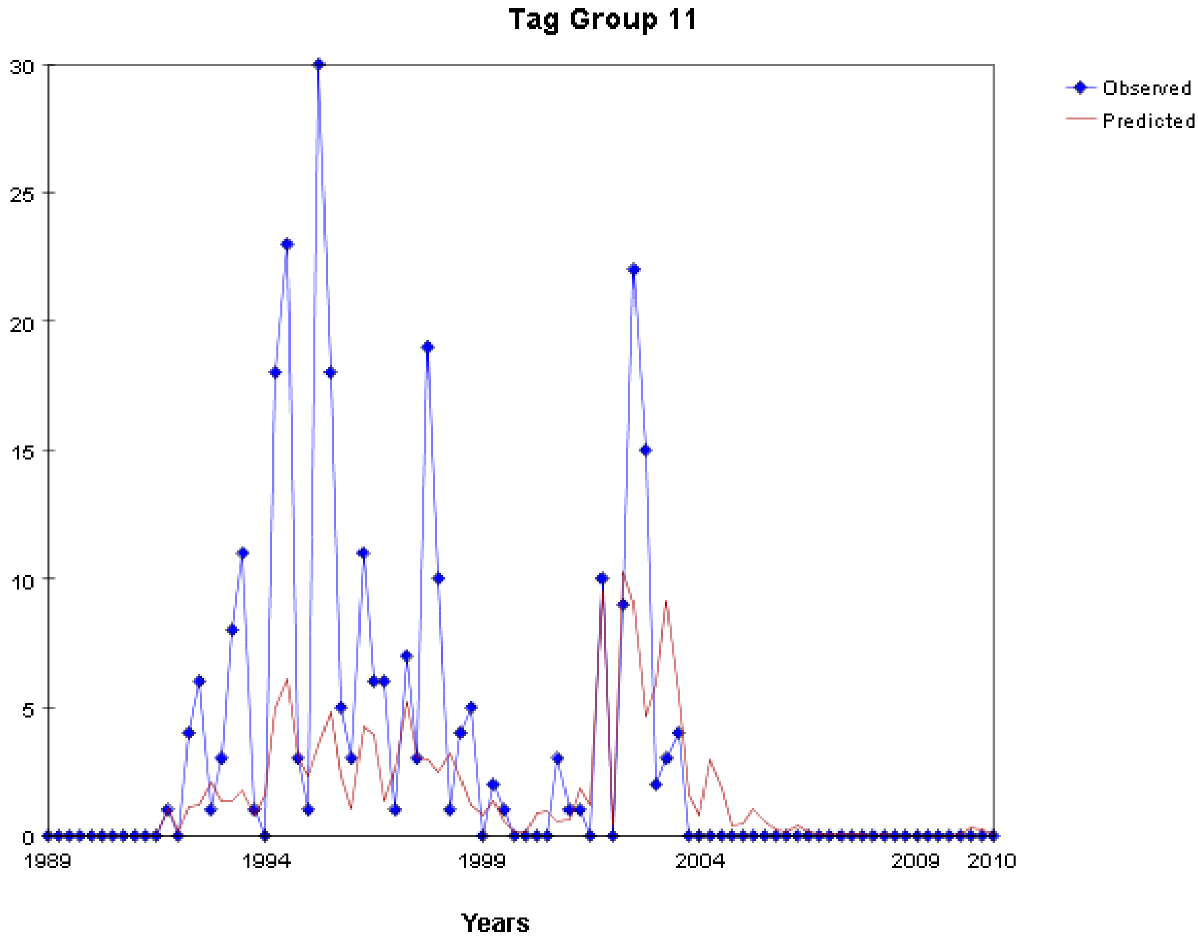


Figure 4: Predicted (brown line) and observed (blue diamonds and line) recaptures of tagged fish by time period at liberty (quarter) in the Australian longline fishery in region 5 (fishery 11).

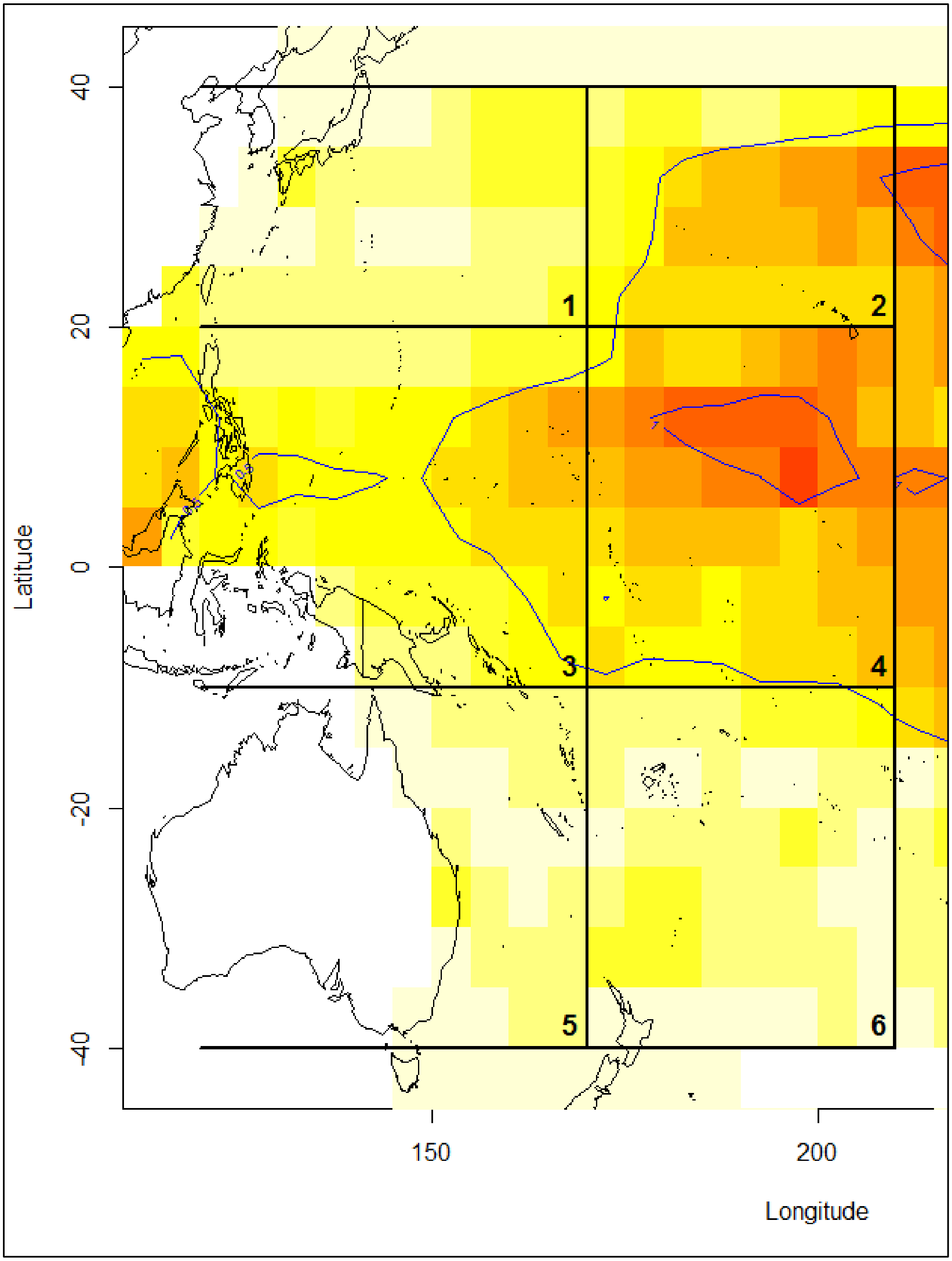


Figure 5: Spatial distribution of bigeye tuna longline fishery catch rates, as estimated in the regional rescaling analysis (Hoyle 2010). Red colour signifies higher catch rates.

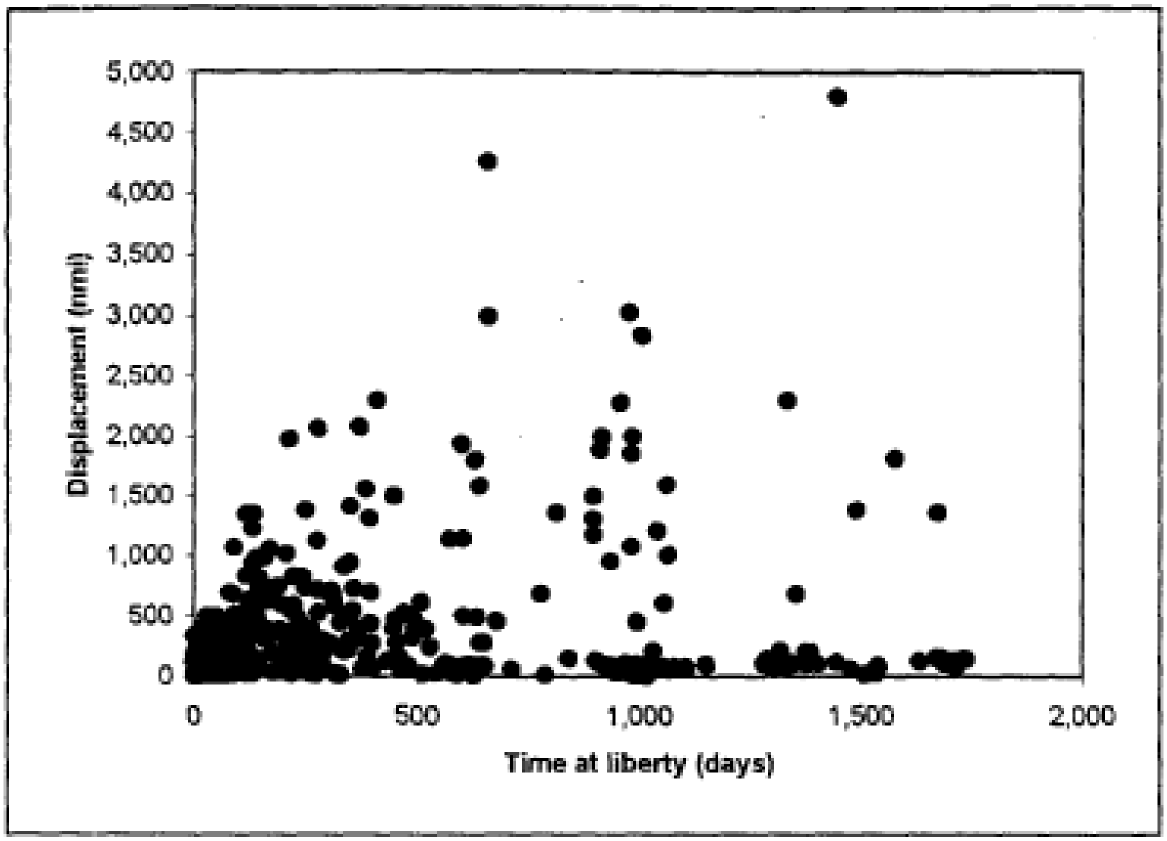


Figure 6: Scatter plot of observed displacement versus time at liberty for RTTP tagged bigeye.

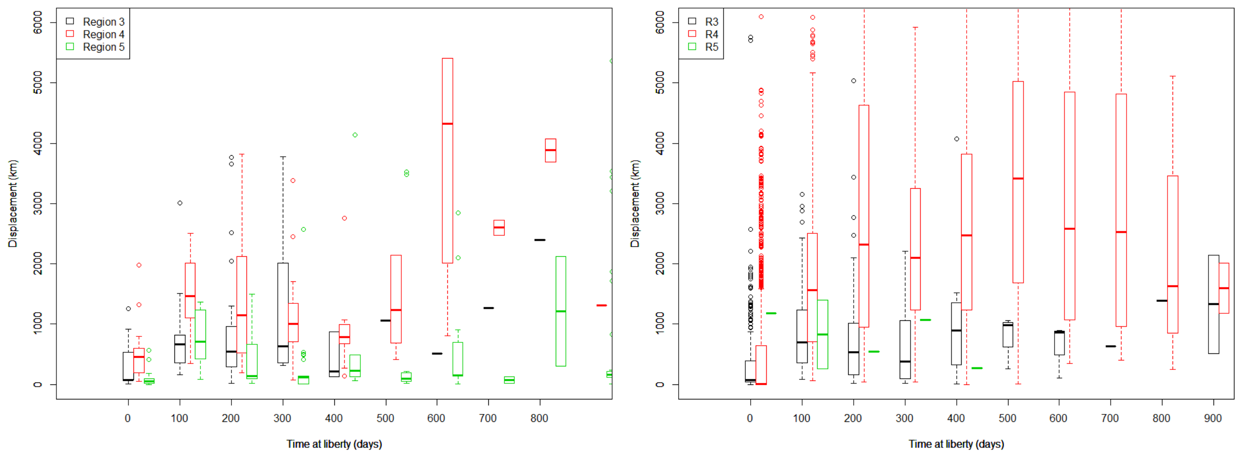


Figure 7: Box plots of observed bigeye displacements by time at liberty and by region of release, for fish tagged in the RTTP (left) and PTTP (right). X-axis labels indicate minimum time at liberty for each group.

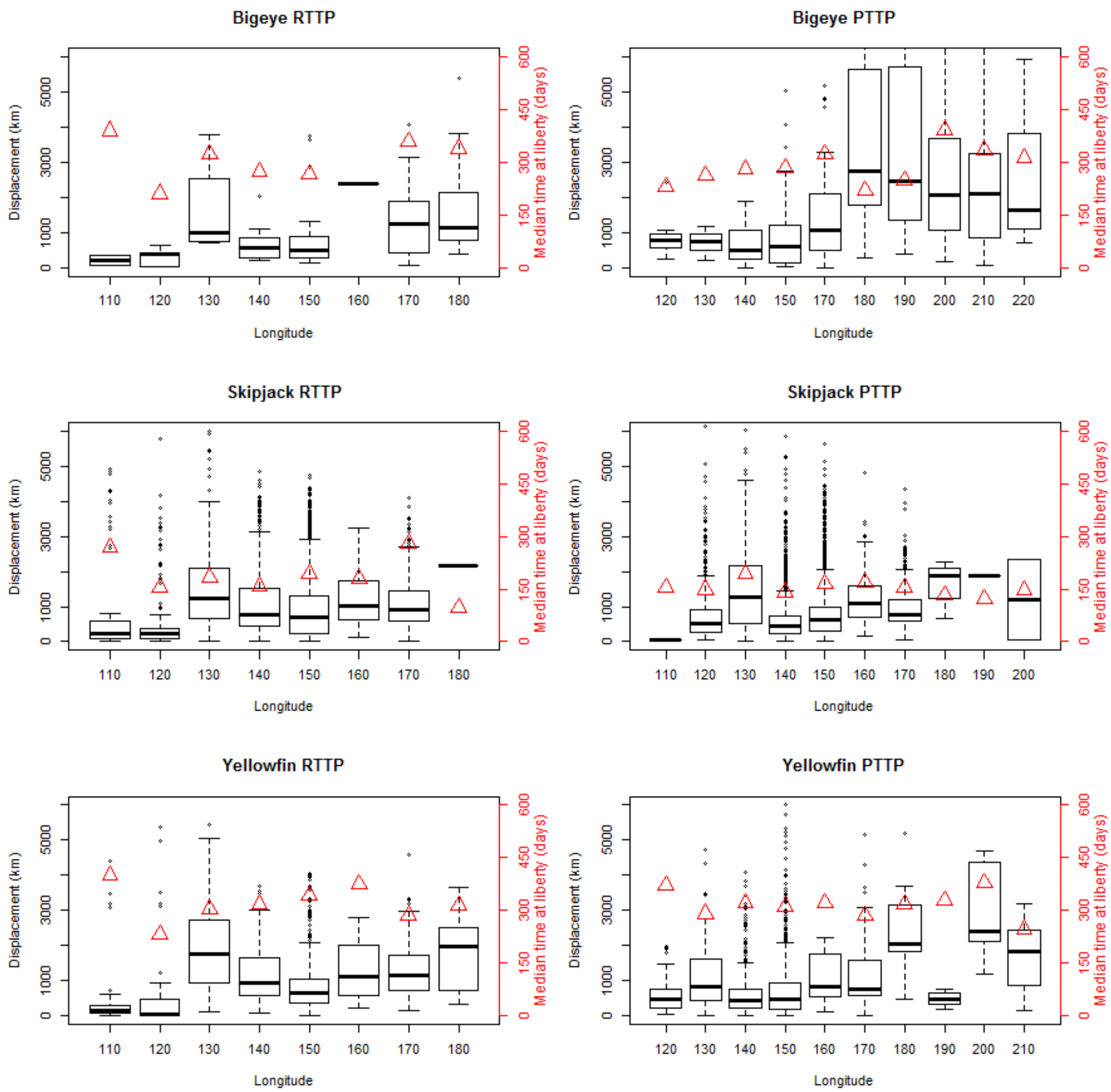


Figure 8: Box plots of observed displacement by release longitude for skipjack, bigeye, and yellowfin tunas for fish with > 183 days at liberty (91 for SKJ), excluding R5, for the RTTP (above) and the PTTP (below). The red triangles represent median times at liberty in days for each longitude group (10 degrees). Longitude labels represent the lower bound of the group.

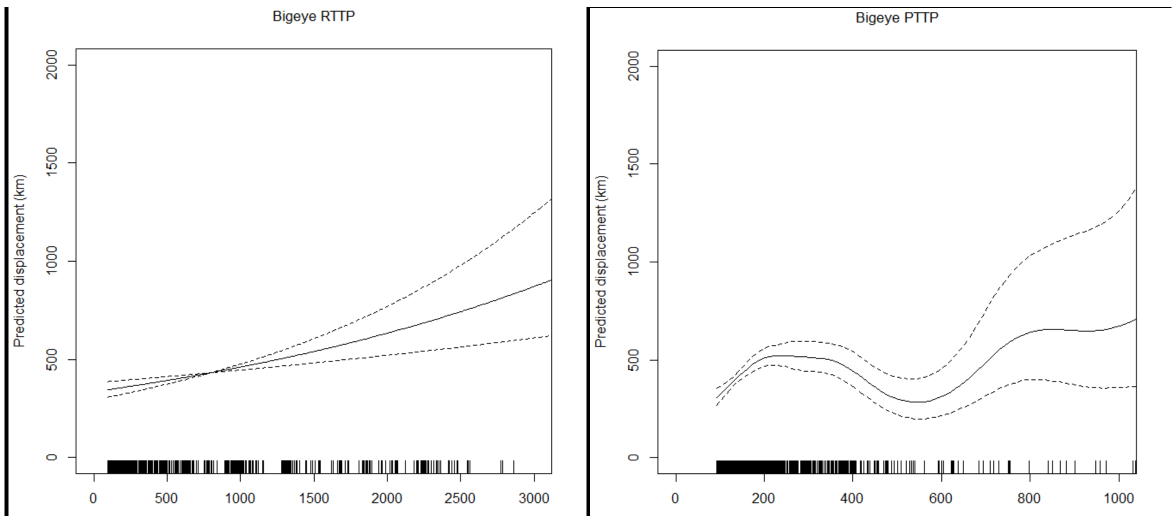


Figure 9: Plots of displacement by time at liberty, predicted for a bigeye of 54 cm at 150E and 0N, estimated by GAMs, for the RTTP (left) and the PTTP (right). Note that given the time since the programme began, recoveries continued up to much greater times at liberty for the RTTP. The dotted lines represent 95% confidence intervals, and the 'rug' on the x axis marks values of the input data.

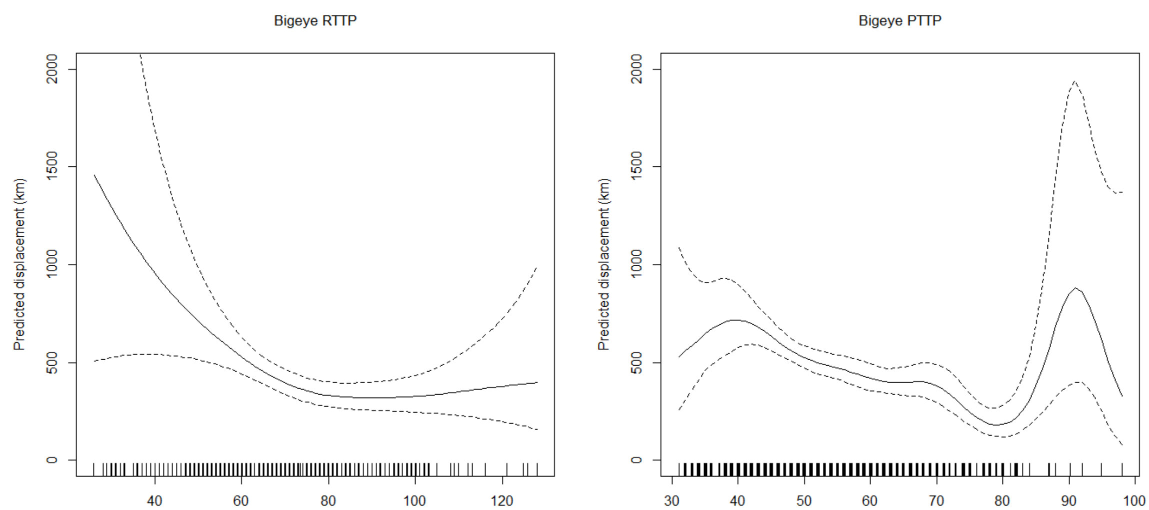


Figure 10: Plots of displacement by length, predicted for a bigeye at 150E and 0N after 1 year at liberty, estimated by GAMs of bigeye length at release, for the RTTP (left) and the PTTP (right). The dotted lines represent 95% confidence intervals, and the 'rug' on the x axis marks values of the input data.

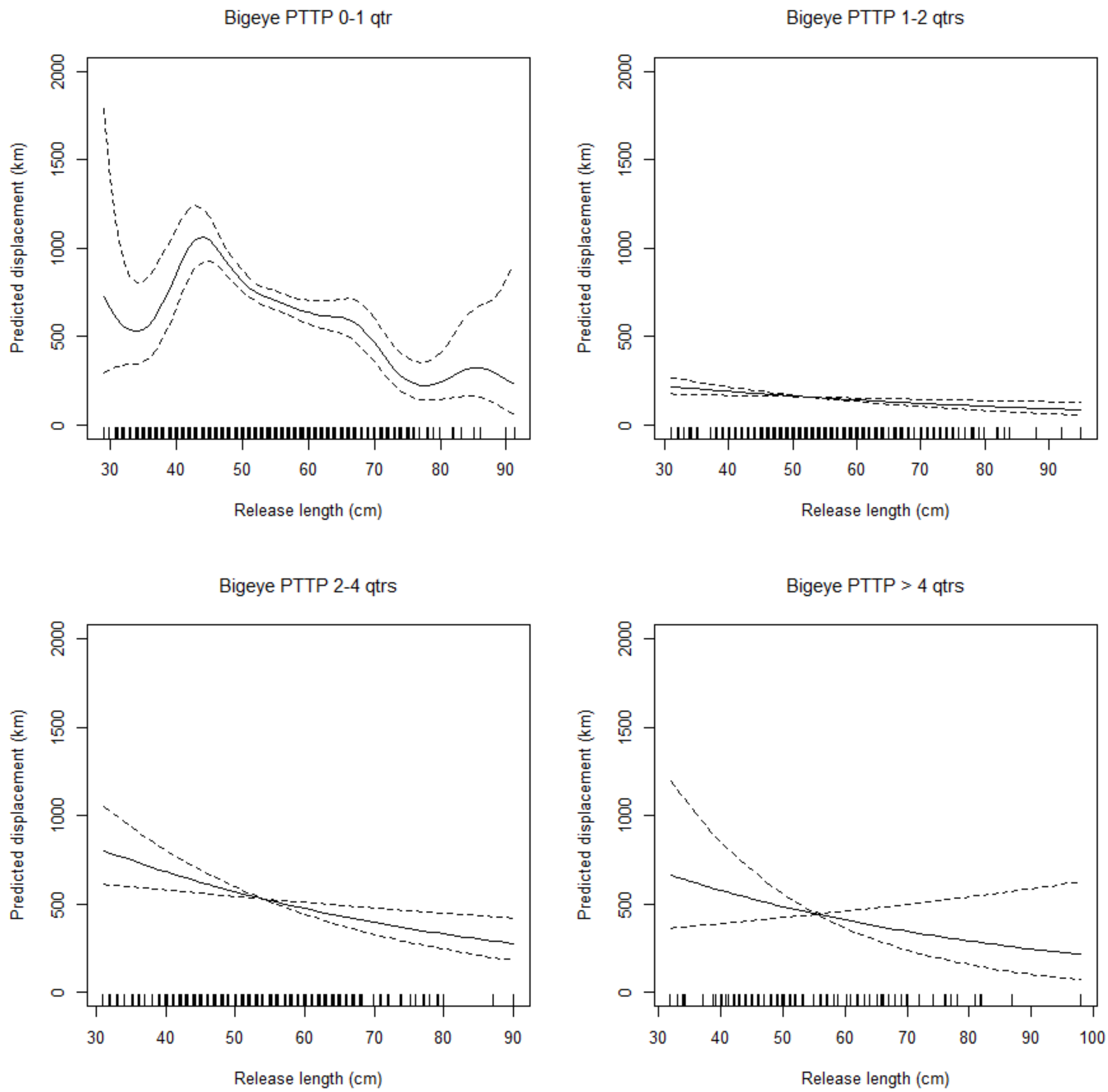


Figure 11: Plots of displacement by length and in groups of days at liberty (0-91, 92-182, 183-365, and more than 365 days) predicted for a bigeye at 150E and 0N after 50, 140, 270, and 500 days at liberty, estimated by GAMs of bigeye length at release, for PTTP releases. The dotted lines represent 95% confidence intervals, and the 'rug' on the x axis marks values of the input data.

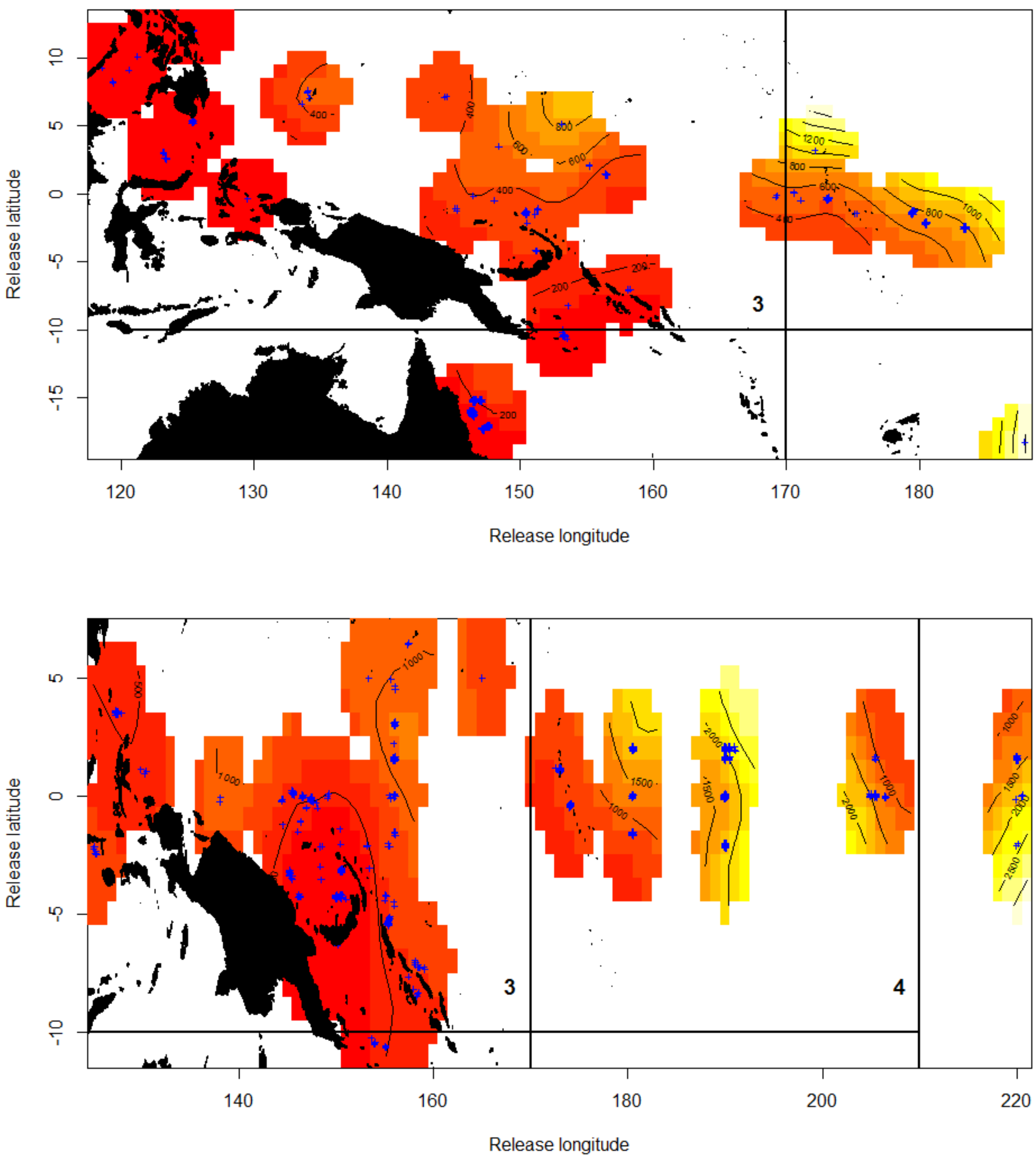


Figure 12: Plots of median displacement by location as estimated by GAMs, for the RTTP (above) and the PTTP (below) for bigeye tuna. Contour lines are at intervals of 200 km (RTTP) or 500 km (PTTP) median displacement. Red indicates smaller displacement. Predictions are for an average length recaptured fish (54cm) after 1 year at liberty. Blue crosses indicate the release locations of tags later recovered. Displacements are predicted for cells within 3 degrees of these locations.

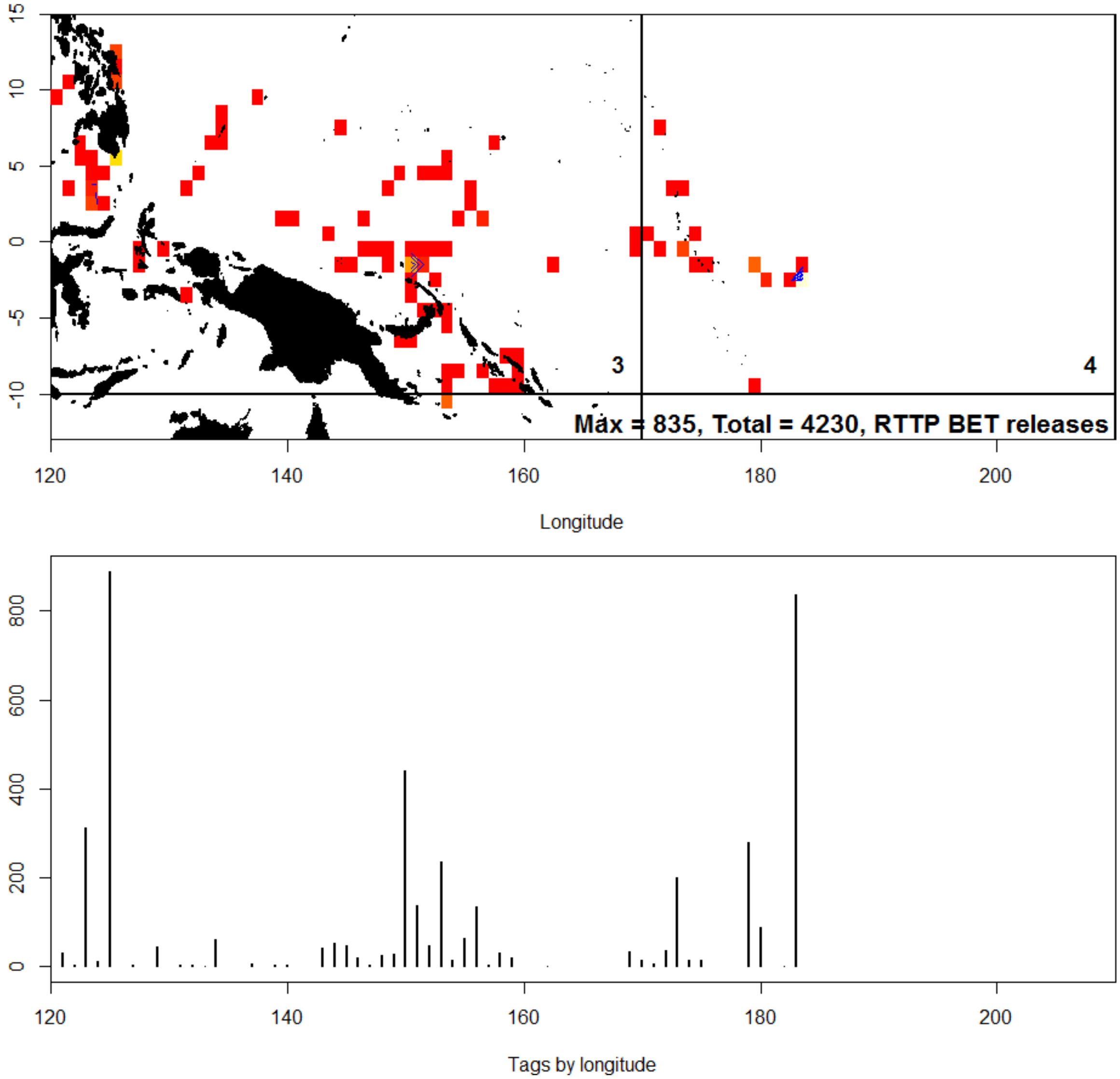


Figure 13: Tag release density map by 1 degree square for bigeye tuna during the RTTP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude.

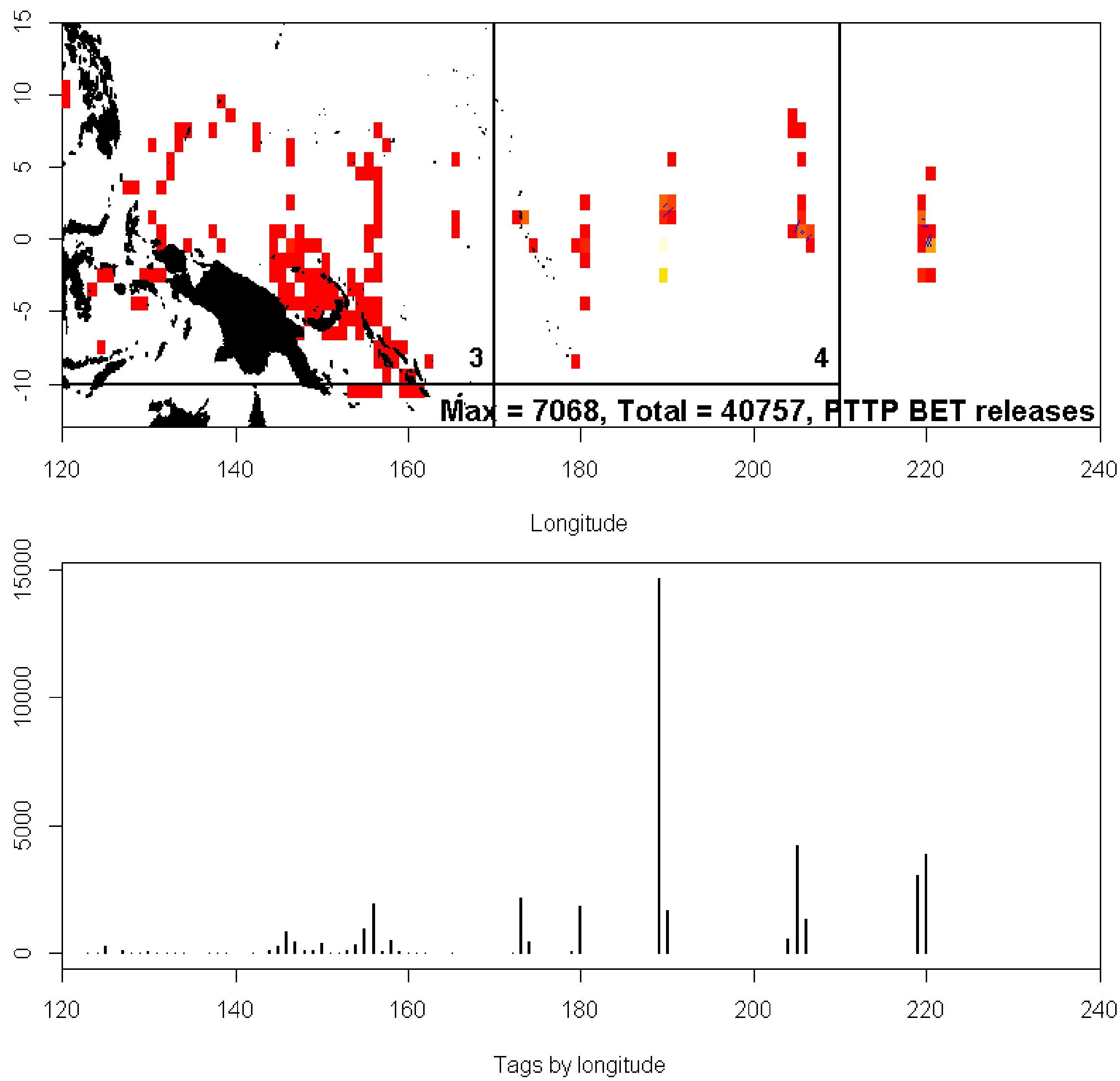


Figure 14: Tag release density map by 1 degree square for bigeye tuna during the PTTP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude.

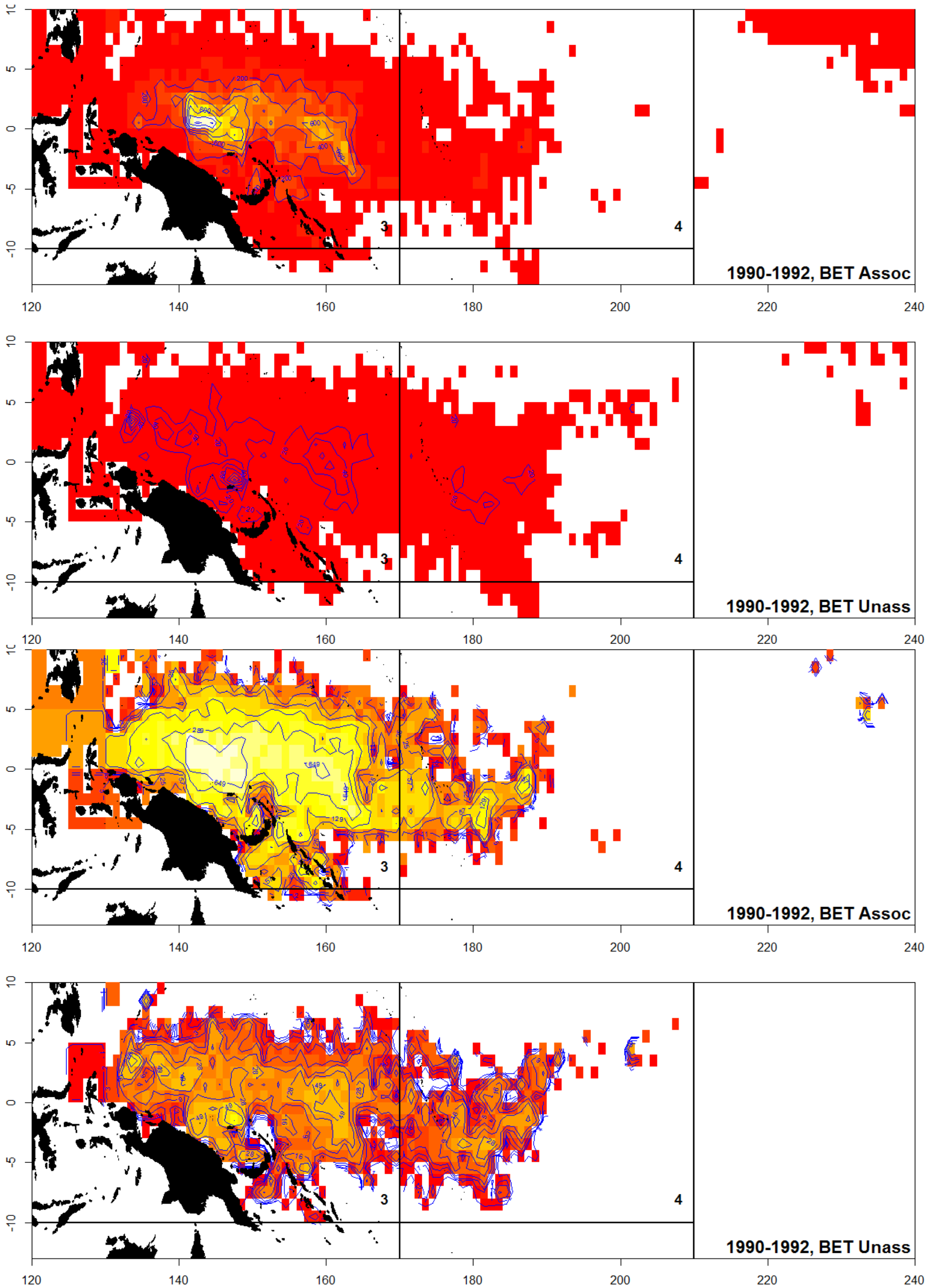


Figure 15: RTTP purse seine catch distribution maps by 1 degree square, by association type, and plotted on nominal (top two) and log (bottom two) scales. Associated and unassociated sets are on the same colour scale but with their own contour intervals. Yellow indicates higher catch. Units are metric tonnes per 1 degree square summed across years.

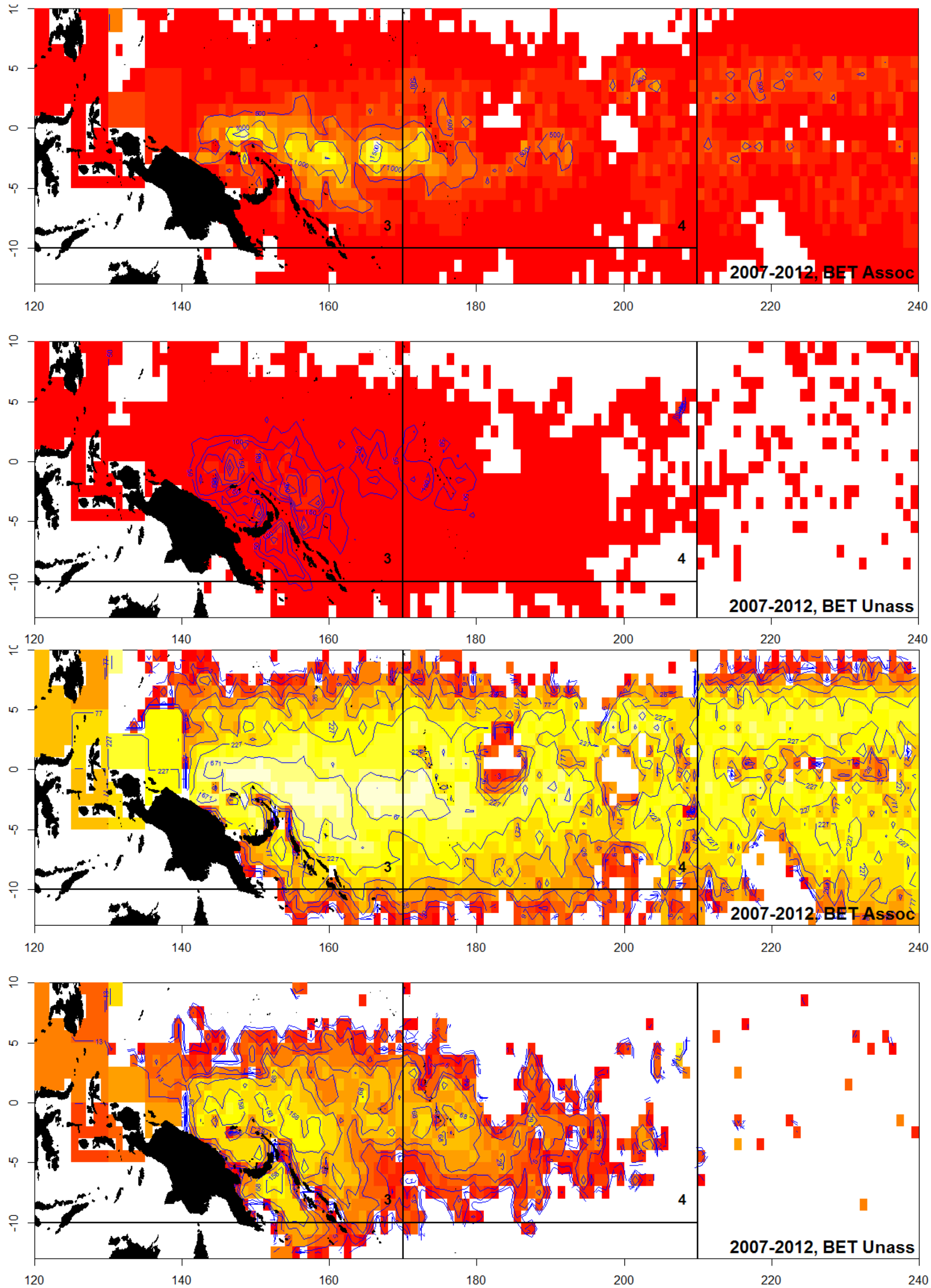


Figure 16: PTTP purse seine catch distribution maps by 1 degree square, by association type, and plotted on nominal (top two) and log (bottom two) scales. Associated and unassociated sets are on the same colour scale but with their own contour intervals. Yellow indicates higher catch. Units are metric tonnes per 1 degree square summed across years.

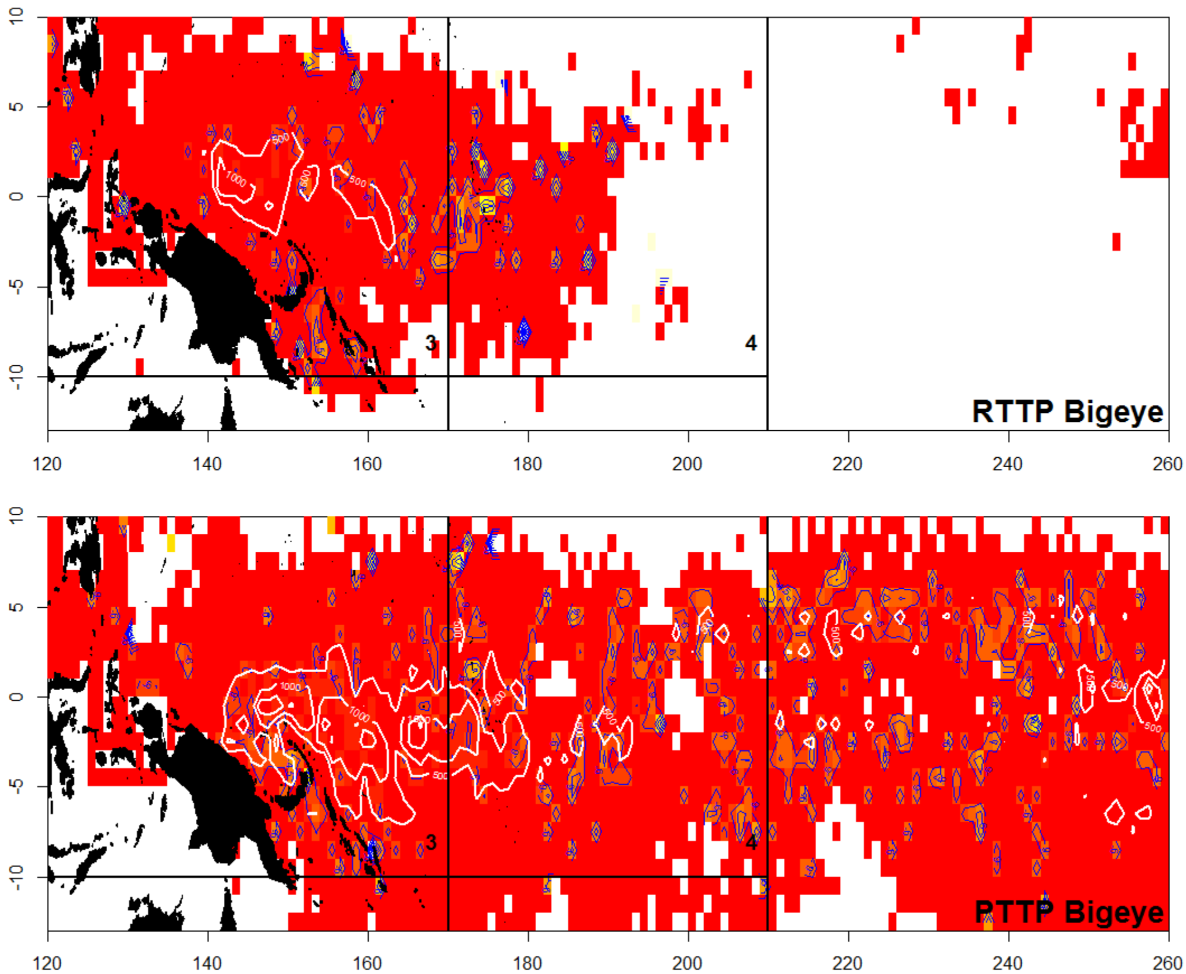


Figure 17: Tag recovery density map per 1 degree square for the RTTP (above) and PTTP (below), for tags recovered after the mixing period. Yellow indicates higher tag density, and responses are on the log scale, so that density increases by a multiple of 4.5 with each blue contour line. The white contour lines indicate the areas of greatest purse seine catch.

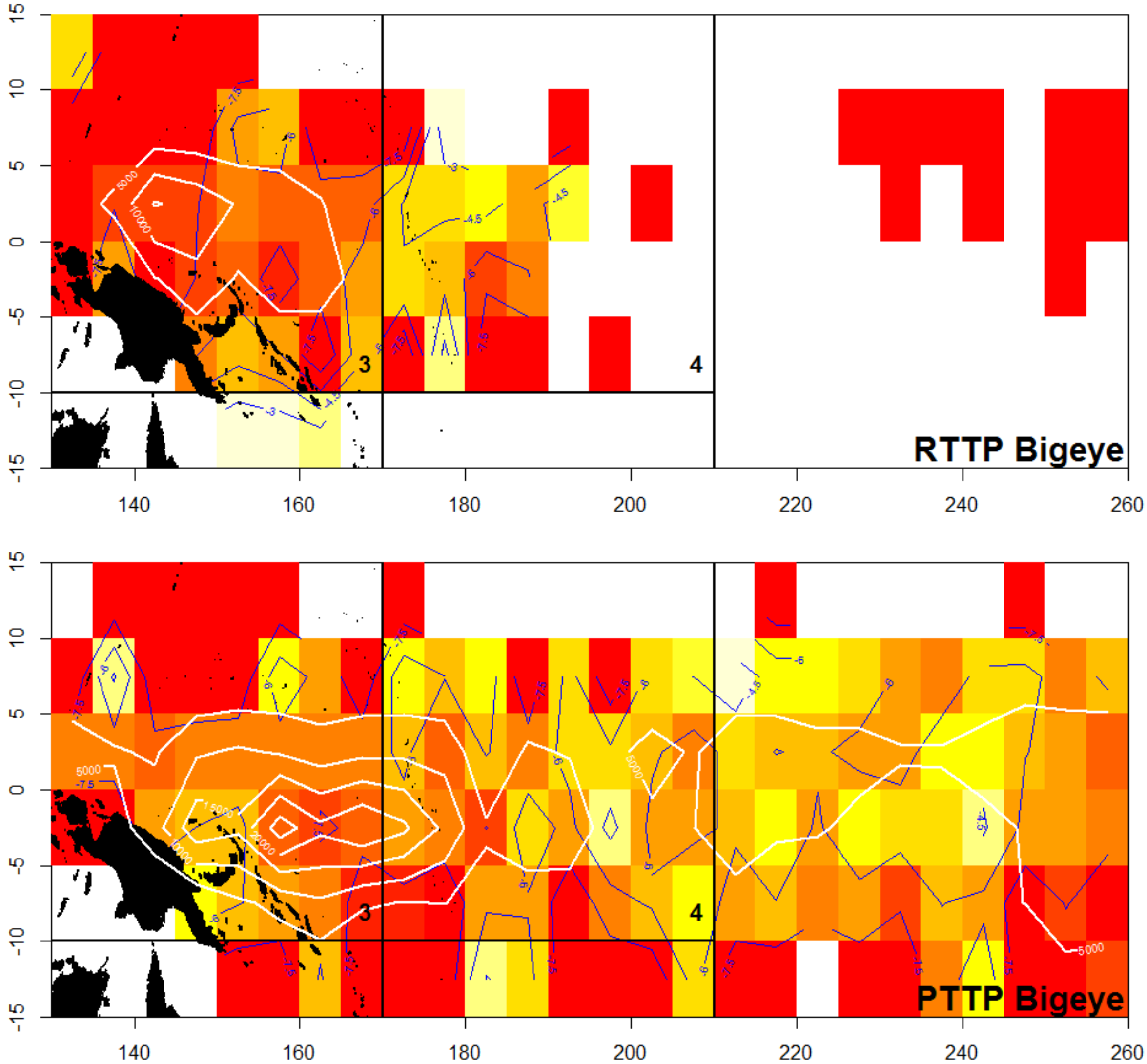


Figure 18: : Tag recovery density map per 5 degree square for the RTTP (above) and PTTP (below), for tags recovered after the mixing period. Yellow indicates higher tag density, and responses are on the log scale, so that density increases by a multiple of 4.5 with each blue contour line. The white contour lines indicate the areas of greatest purse seine catch.

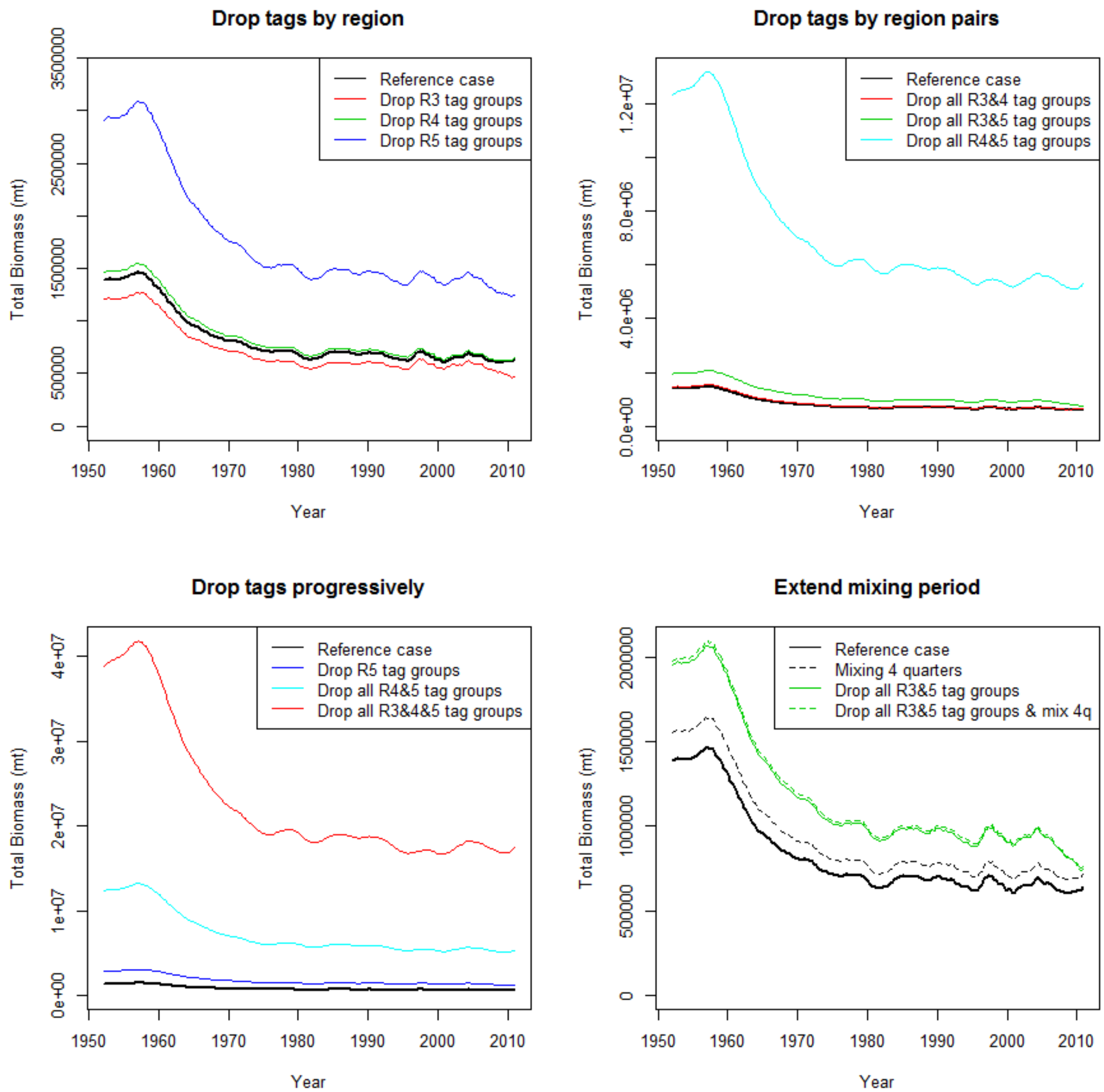


Figure 19: Bigeye tuna total biomass by region estimated in the reference case of the 2011 bigeye assessment (black) versus dropping tags from one or more regions (first three panels) or extending the mixing period from 2 quarters to 4 quarters (bottom right panel).

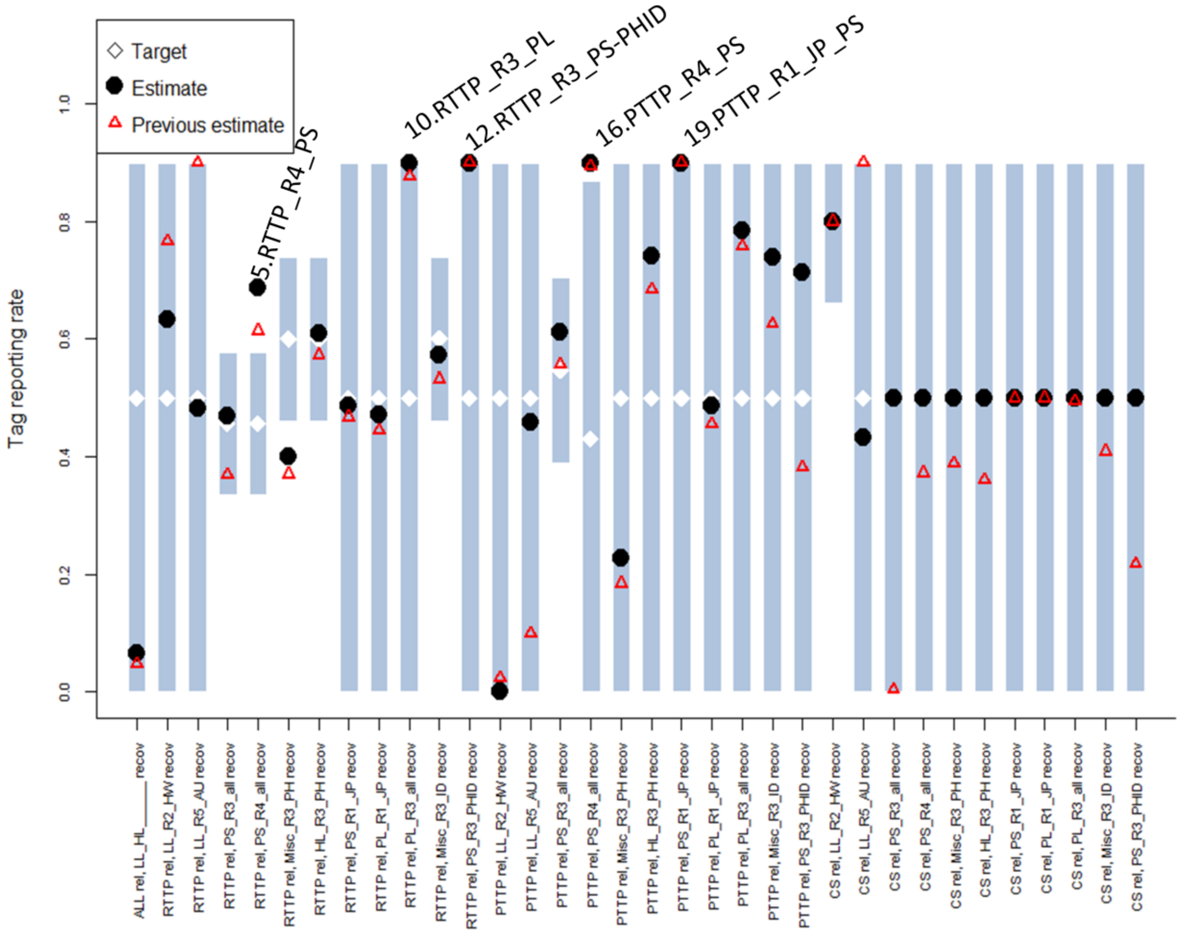


Figure 20: Estimated reporting rates both before (red triangles) and after (black dots) removing region 5 tags from the bigeye assessment. The 'target' is the mode of the prior.

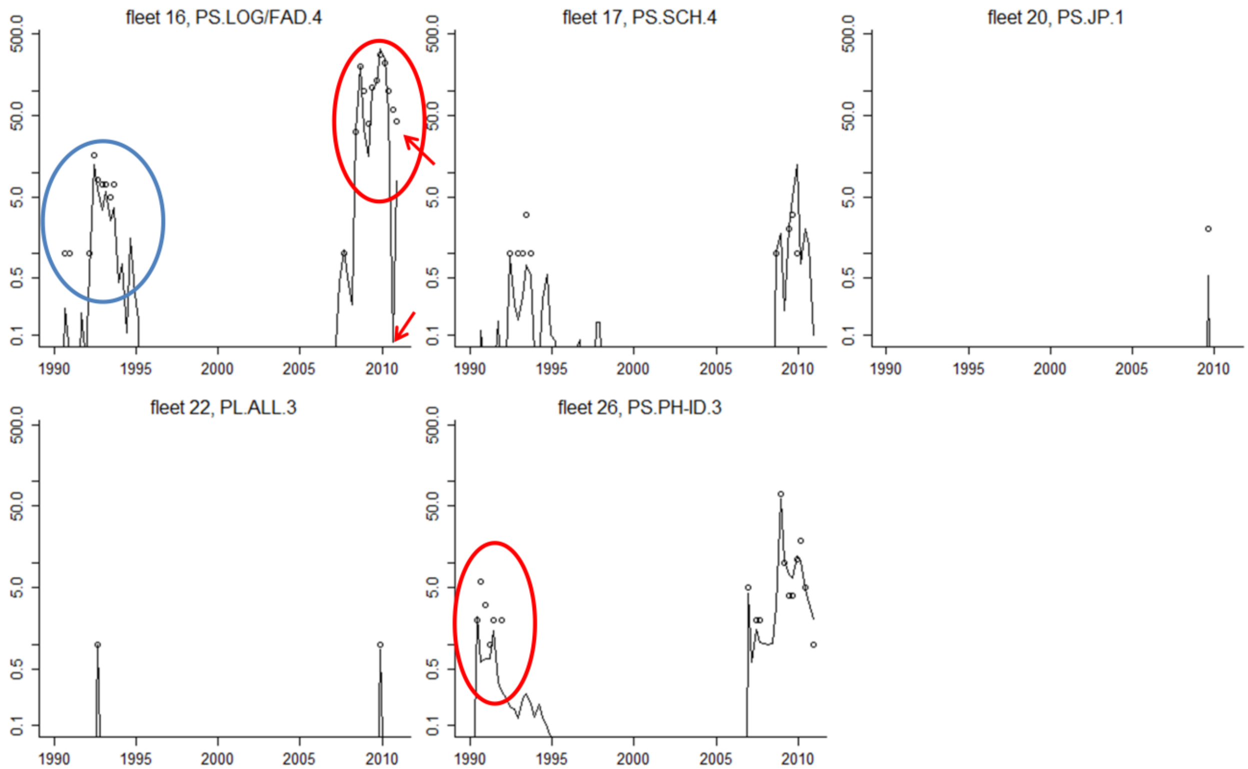


Figure 21: Observed (black circles) and expected (black lines) tag returns from the bigeye assessment after removing region 5 tags, for fisheries with reporting rates on or near the 0.9 boundary. The red circles indicates periods that include larger mismatches between observed and expected tags, in the region 4 purse seine fishery for tags released in the PTTP, and in the region 3 Philippines-Indonesia purse seine fishery for tags released in the RTTP. The other fisheries observe relatively few excess tags.

Appendix A

Methods

The methods for skipjack and yellowfin are as described for bigeye.

Results and Discussion

Yellowfin observed displacements by time at liberty and region for the RTTP were largest on average for region 4 releases (Figure 22). However, observed displacements for tags released in regions 3 and 5 were similar to one another. During the PTTP the observed displacements for tags released in region 5 were similar to those for region 4, while observed displacements were consistently smallest for tags released in region 3.

Observed displacements for skipjack in both the RTTP and PTTP increased for a period (200-300 days) and then were generally stable (Figure 23). Yellowfin in both the RTTP and PTTP showed long term increases in displacement with time, out to 1000 days in both cases.

For skipjack tuna in the RTTP there was little variation with release length, while for the PTTP the observed displacement increased with length at release (Figure 24). Yellowfin observed displacements by length varied more than the other two species, with a tendency for displacements to be smaller for larger fish. Observed displacements by length at release may be affected by the selectivities of the fisheries that catch each species, as well as the species' movement rates at length.

There were some consistencies in the spatial patterns of observed displacements among the three species and two tagging programs (Figure 25 and Figure 26). Observed displacements were smaller in the Indonesia-Philippines area for all three species, and also in the Bismarck Sea - Solomon Islands area. Observed displacements will be affected by the distribution of the fishing effort as well as the movements of the fish.

PTTP tag release densities were quite aggregated in region 3 and in the PNG Solomon Islands area, since many of the releases were associated with the PNG tuna tagging programme (Figure 29 and Figure 32).

Tag recovery densities for skipjack (Figure 37) and yellowfin (Figure 38) tags showed a continuous pattern, but with strong spatial variation. Higher densities were observed closer to locations with more releases, in both the RTTP and PTTP. Qualitatively, yellowfin tag density appears to be more aggregated than skipjack densities.

For the yellowfin stock assessment, dropping tag groups had moderate effects on average biomass estimates (Figure 41), but far less substantial than for the bigeye assessment (Figure 20). Removing the region 2, 4, or 5 tag releases resulted in higher biomass estimates, while as for bigeye, removing region 3 releases resulted in lower biomass estimates. When removing releases from region pairs, both pairs that included dropping region 3 releases lowered the biomass estimates, while removing region 4 and 5 releases together resulted in higher biomass estimates. Progressively dropping tag releases from region

5, region 3, region 4, and region 2 resulted in a final biomass trend quite close to the model with all tag releases included. It may be the case that the upward pressure on the biomass estimate from the region 3 tag releases is similar to the combined downward pressure from the region 2, 4, and 5 tag releases. Removing all of the yellowfin tags resulted in a similar population trend to the model with all tags included. Overall this suggests that tag dynamics by region are not really consistent with each other, or the other data in this stock assessment model, but by including tags from all regions, the influences of the tagging data balance out in the sense that the aggregate biomass resembles the assessment without any tags.

Changing the mixing period for yellowfin from 2 quarters to 4 quarters changed the biomass estimates more than removing tags from any individual region. Rather than indicating greater mixing after a long period, this result reflects the poor fit of the tagging data with longer periods at liberty. Figure 32 of the 2011 stock assessment (Langley, Hoyle SD, & Hampton 2011) shows that many fewer tags are observed than expected for periods at liberty of 5 or more quarters. To the model, these lower return rates are consistent with a higher biomass, which is why extending the mixing period increases the biomass. The catch distribution (and) and tag density maps (Figure 17 and) above suggest one possible explanation: in reality, due to the displacement rate of yellowfin and the tagging locations, the tags may be caught more in associated (smaller YFT) than in unassociated (larger YFT) fisheries. Associated and unassociated tags are pooled in the model, so the model cannot allow for different catch rates of the fisheries with different reporting rates. Associated and unassociated catches may also have different reporting rates, since the PS fleets specialise to some extent, which may compound the problem. At this time it is difficult to evaluate the confounding implications of reporting rate assumptions, because tag seeding experiments have been limited. It seems likely that reporting rates would vary more by landing port than fishing fleet.

Figures

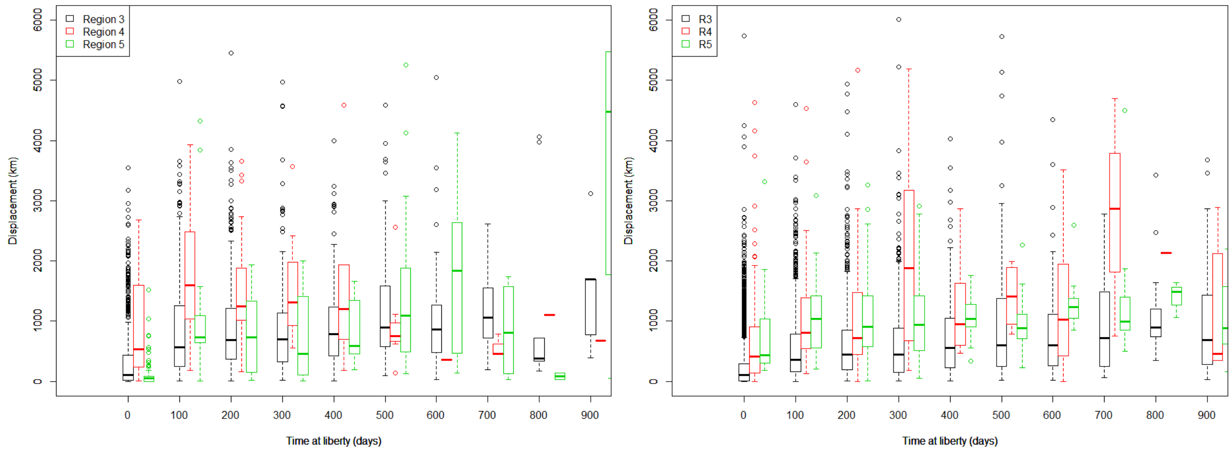


Figure 22: : Box plots of observed yellowfin displacements by time at liberty and by region of release, for fish tagged in the RTTP (left) and PTTP (right). X-axis labels indicate minimum time at liberty for each group.

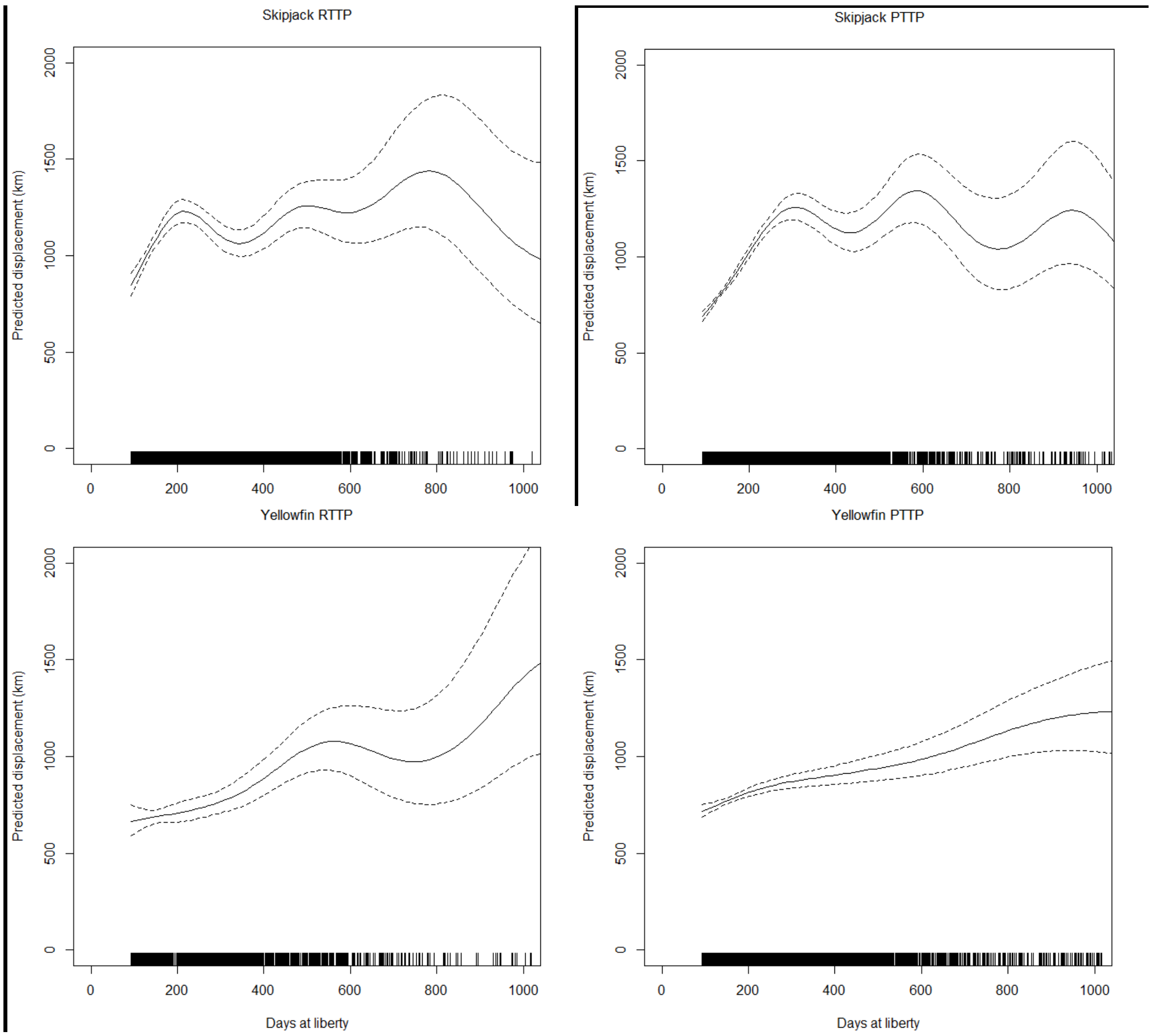


Figure 23: : Plots of median displacement by time estimated by GAMs, for the RTTP (left) and the PTTP (right and for skipjack (above) and yellowfin (below) tunas. Predictions are for an average length recaptured fish (47cm RTTP and 44cm PTTP skipjack; 43cm yellowfin) released at 150E, 0N. The dotted lines represent 95% confidence intervals, and the 'rug' on the x axis marks values of the input data.

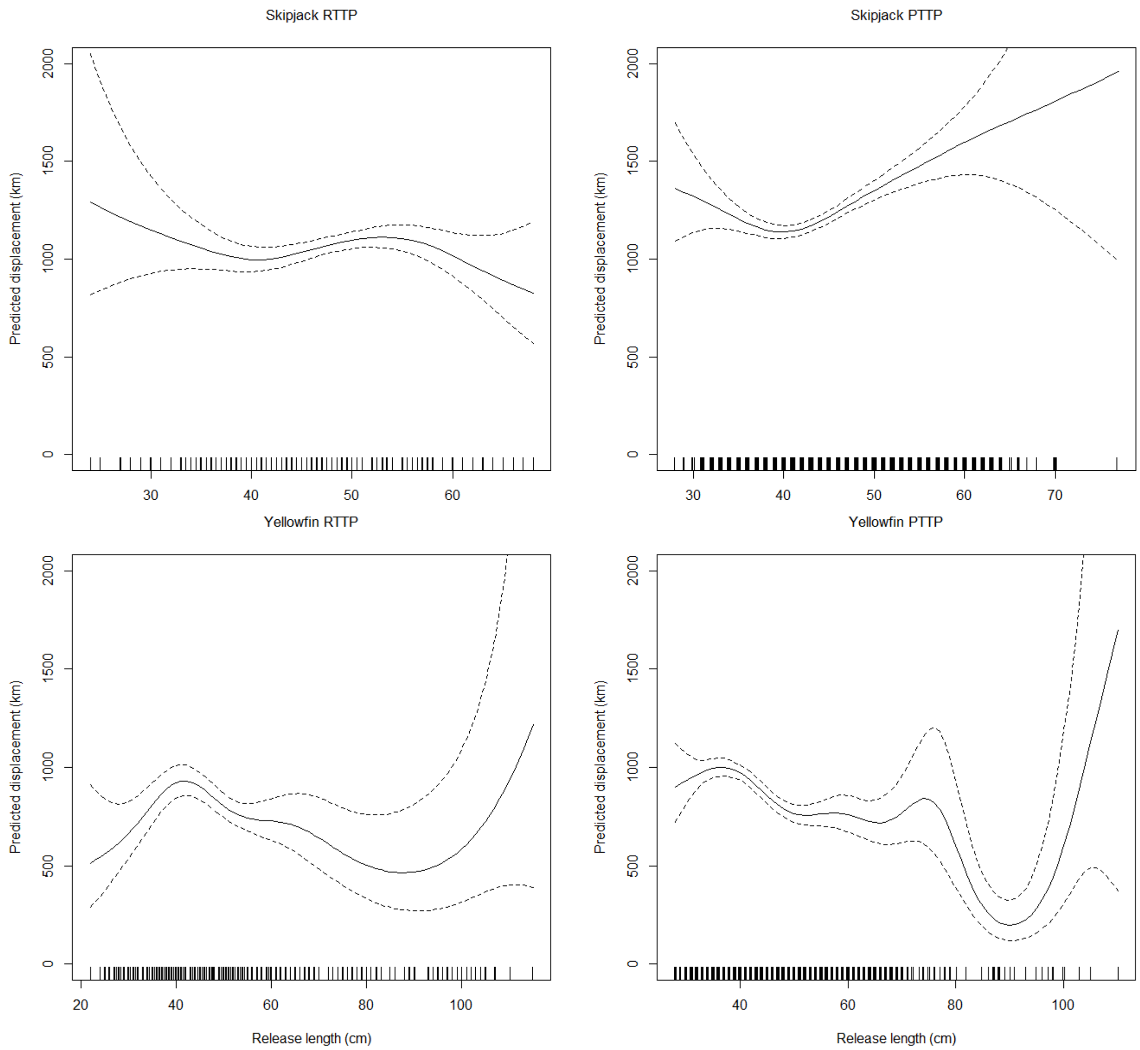


Figure 24: Plots of the contribution to displacement estimated by GAMs of fish length at release, for the RTTP (left) and the PTTP (right) and for skipjack (above) and yellowfin (below) tunas. Predictions are for a fish released at 150E, 0N and recaptured after 1 year at liberty. The dotted lines represent 95% confidence intervals, and the 'rug' on the x axis marks values of the input data.

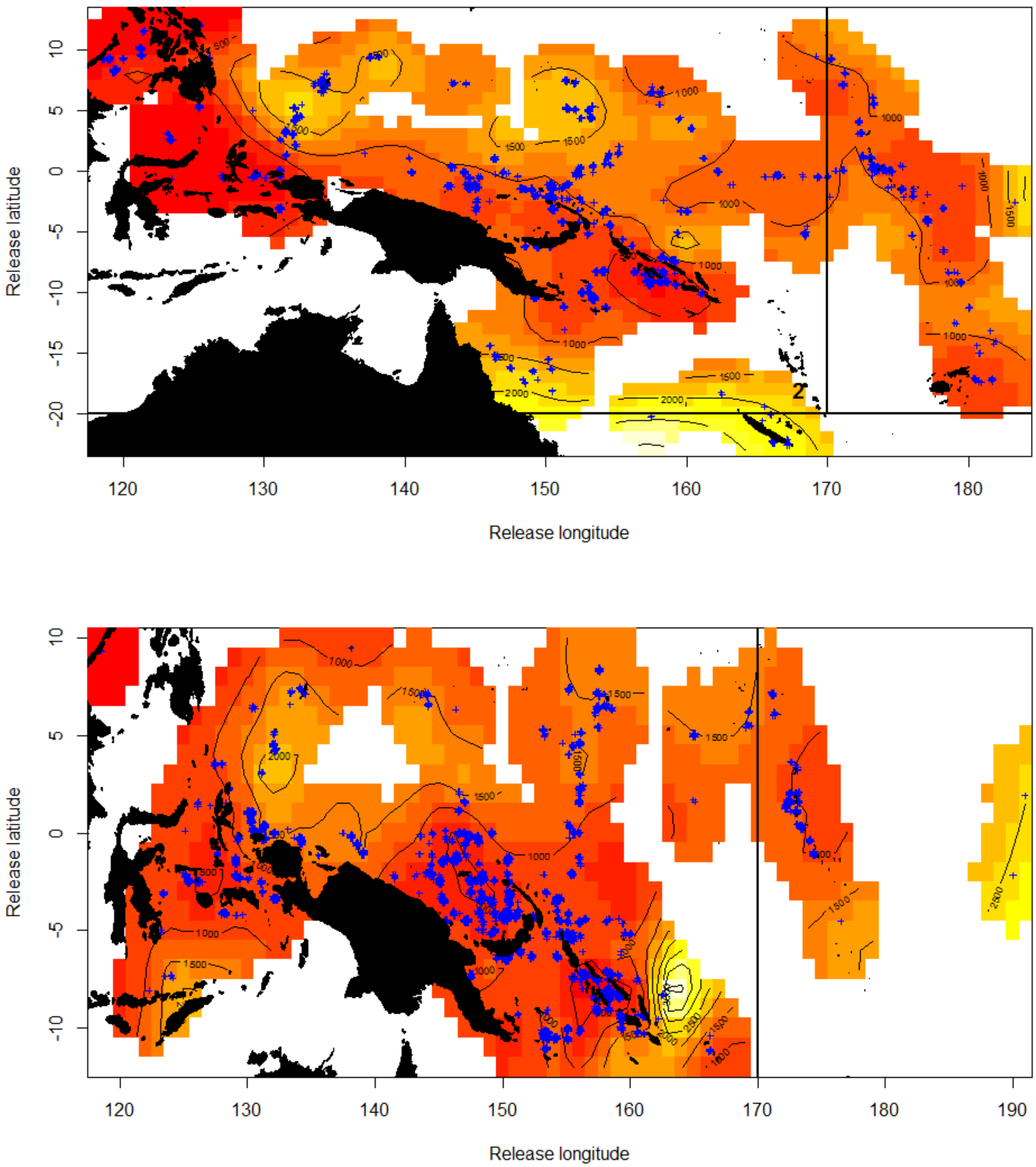
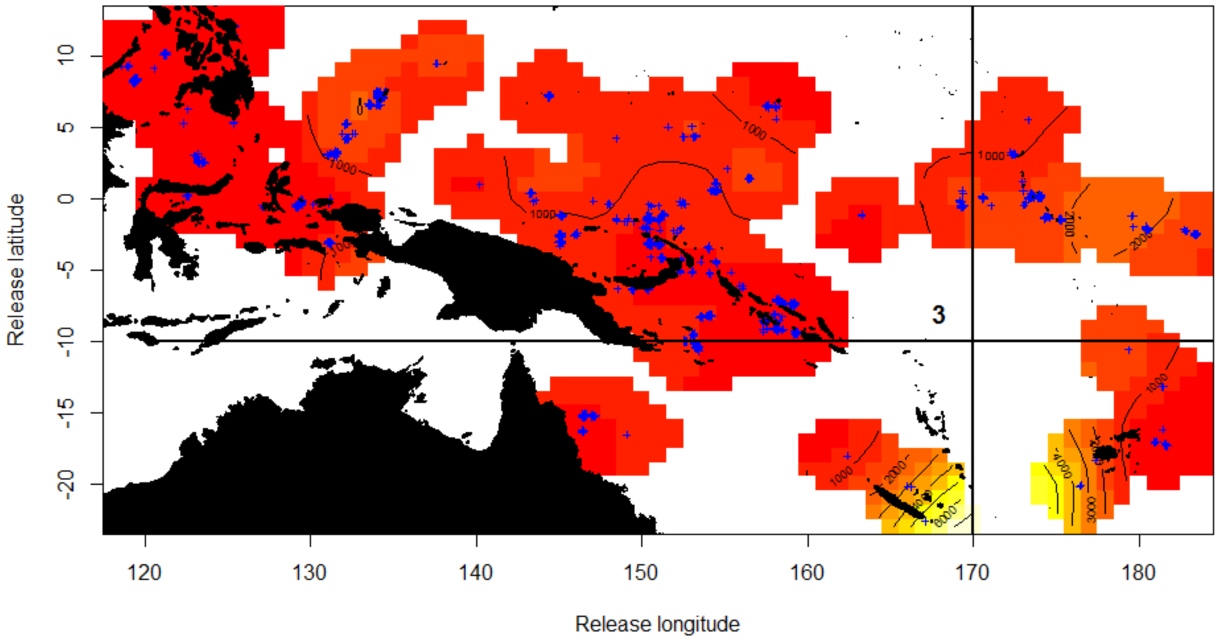


Figure 25: Plots of median displacement by location as estimated by GAMs, for the RTTP (above) and the PTTP (below) for skipjack tuna. Contour lines are at intervals of 200 km (RTTP) or 500 km (PTTP) median displacement. Red indicates smaller displacement. Predictions are for an average length recaptured fish (47cm RTTP and 44cm PTTP) after 1 year at liberty. Blue crosses indicate the release locations of tags later recovered. Displacements are predicted for cells within 3 degrees of these locations.



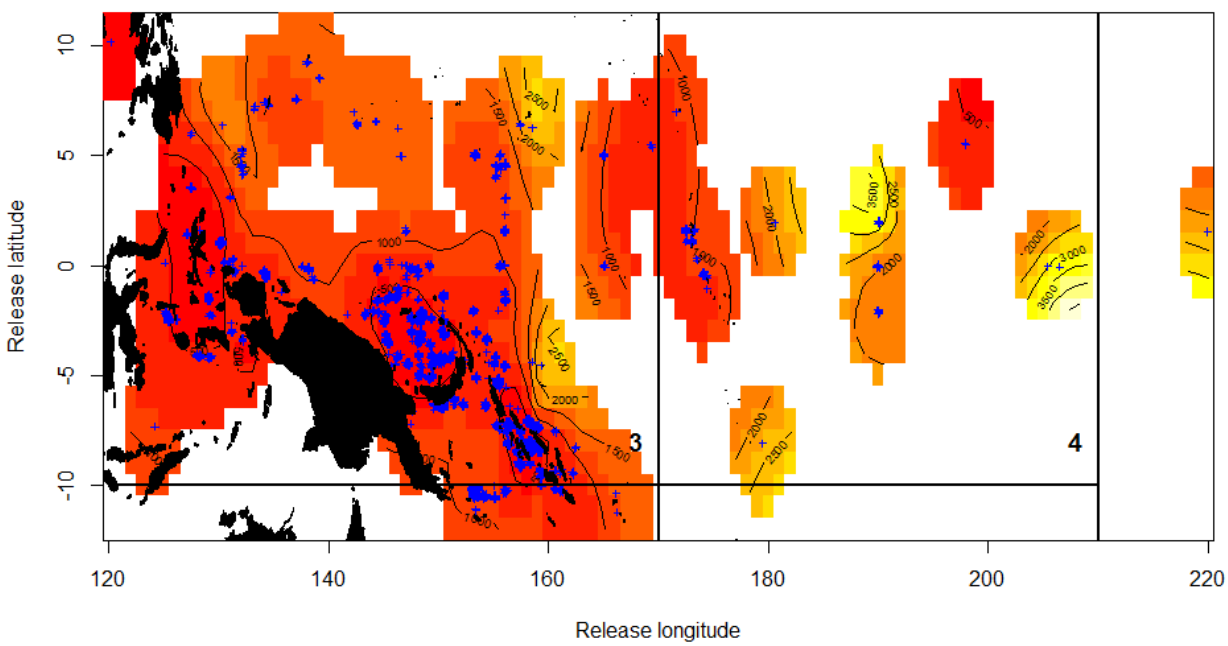


Figure 26: Plots of median displacement by location as estimated by GAMs, for the RTTP (above) and the PTTP (below) for yellowfin tuna. Contour lines are at intervals of 500 km median displacement. Red indicates smaller displacement. Predictions are for an average length recaptured fish (43cm in both cases) after 1 year at liberty. Blue crosses indicate the release locations of tags later recovered. Displacements are predicted for cells within 3 degrees of these locations.

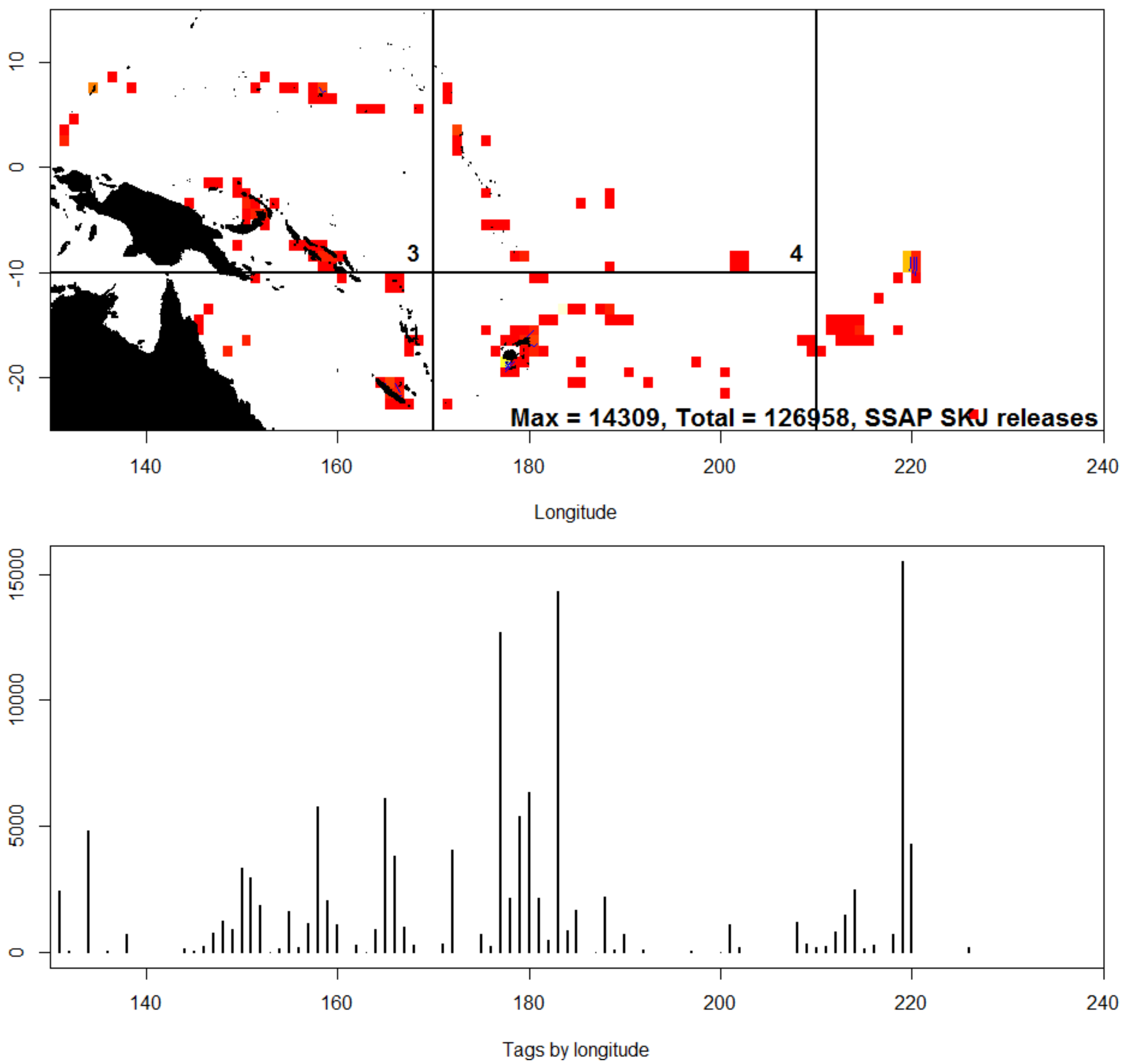


Figure 27: Tag release density map by 1 degree square for skipjack tuna during the SSAP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude. A limited number of tags were entered south and (a few) north of the boundaries.

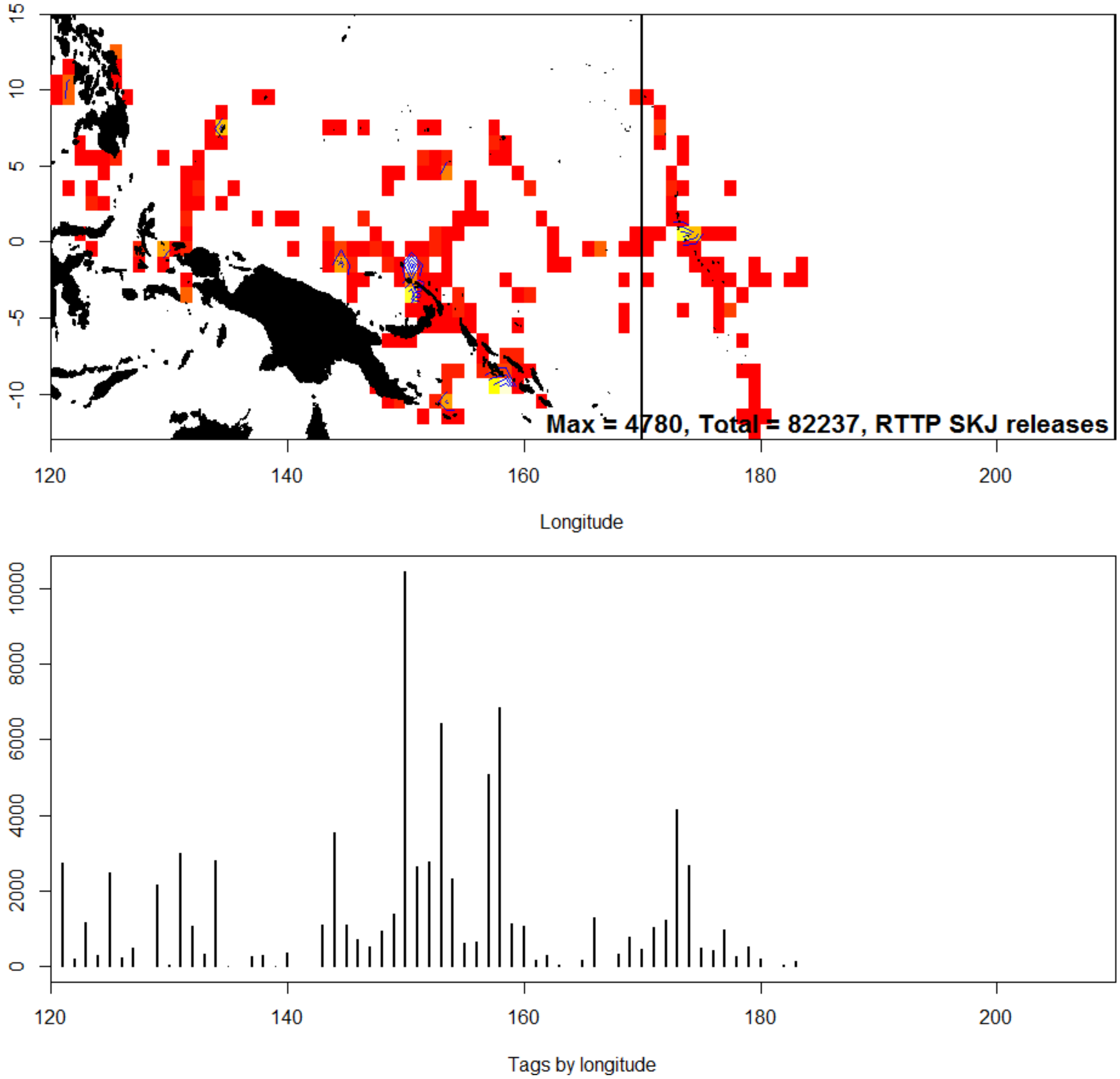


Figure 28: Tag release density map by 1 degree square for skipjack tuna during the RTTP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude.

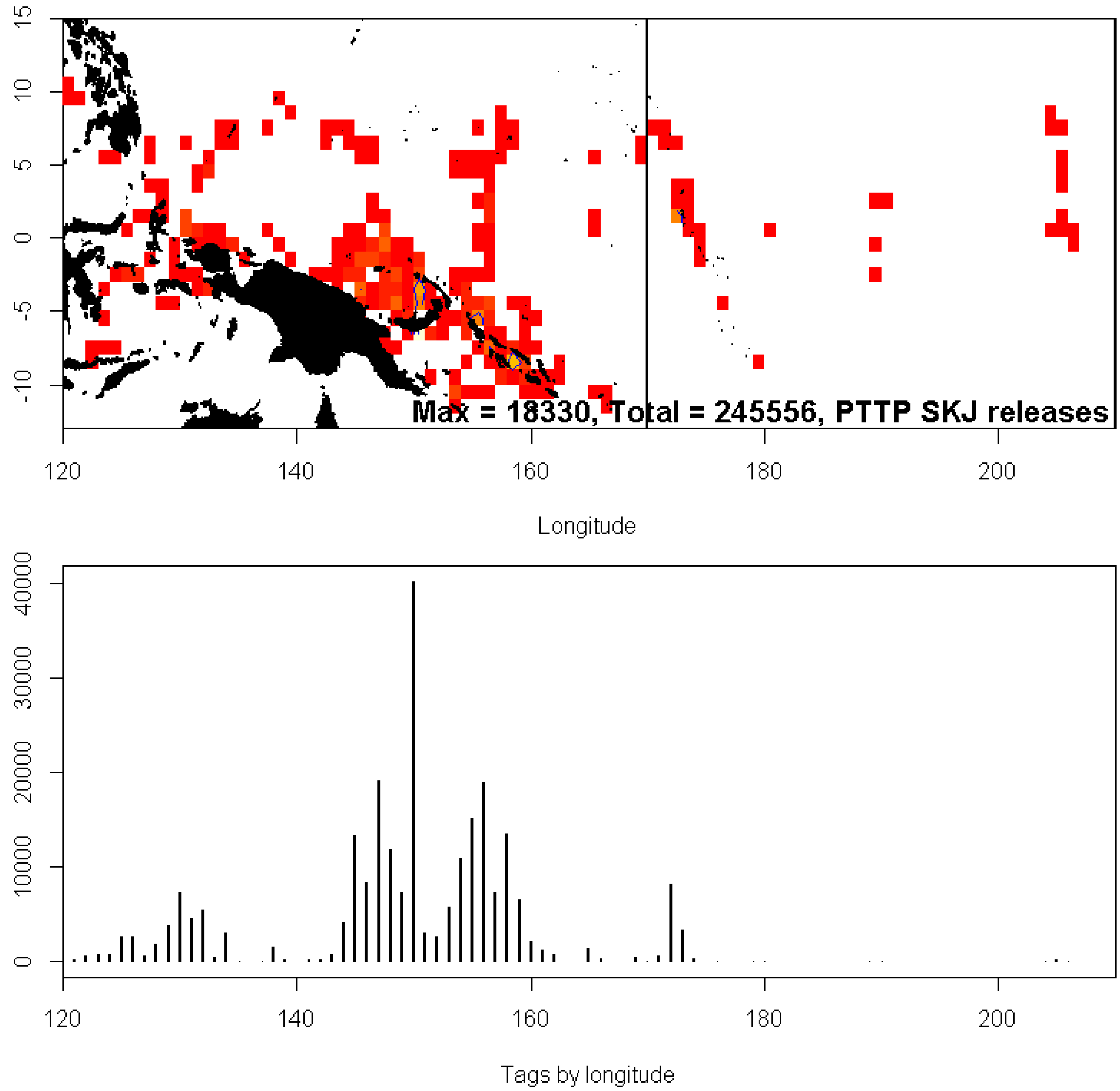


Figure 29: Tag release density map by 1 degree square for skipjack tuna during the PTTP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude.

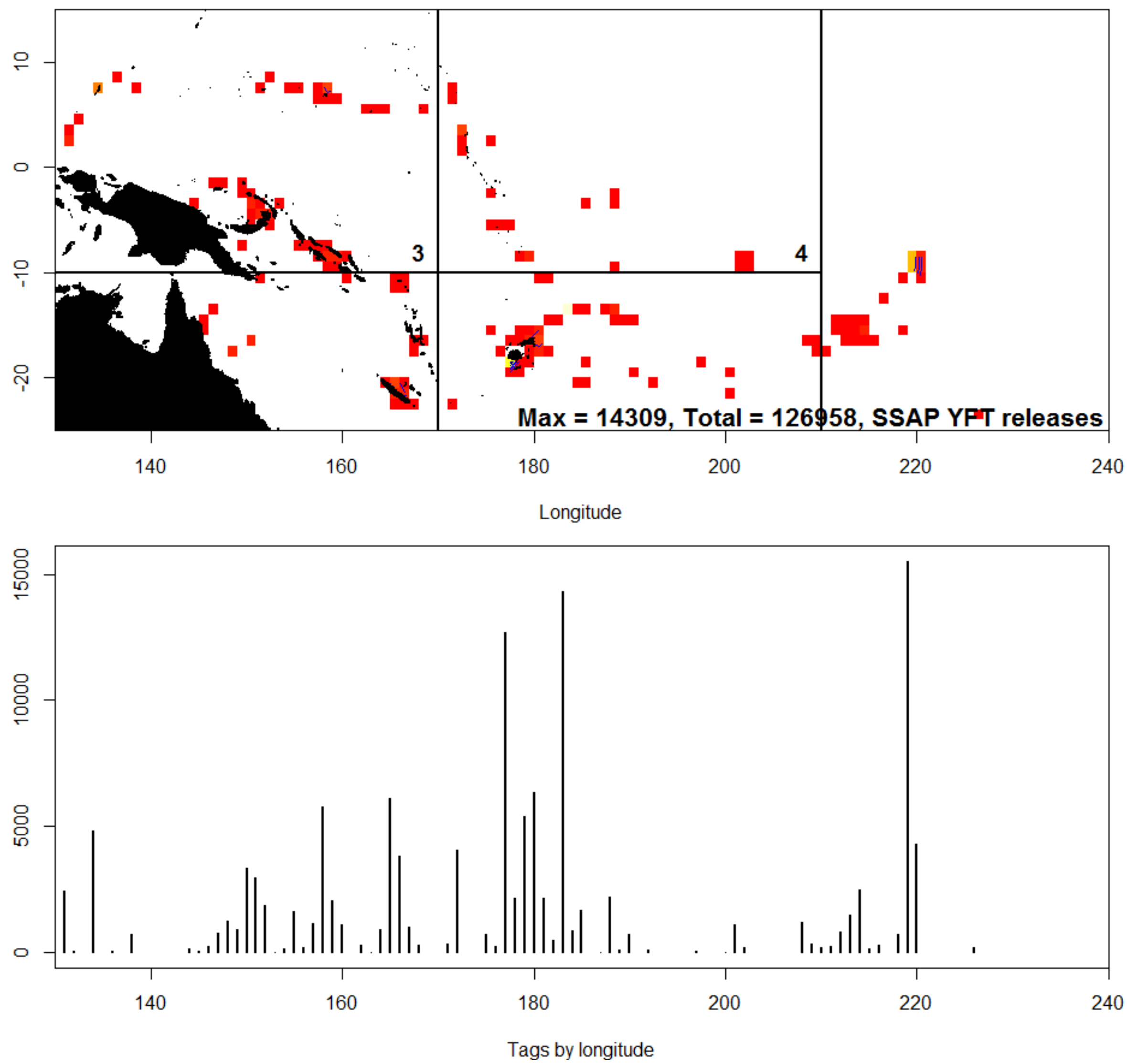


Figure 30: Tag release density map by 1 degree square for yellowfin tuna during the SSAP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude. A limited number of tags were entered south and (a few) north of the boundaries.

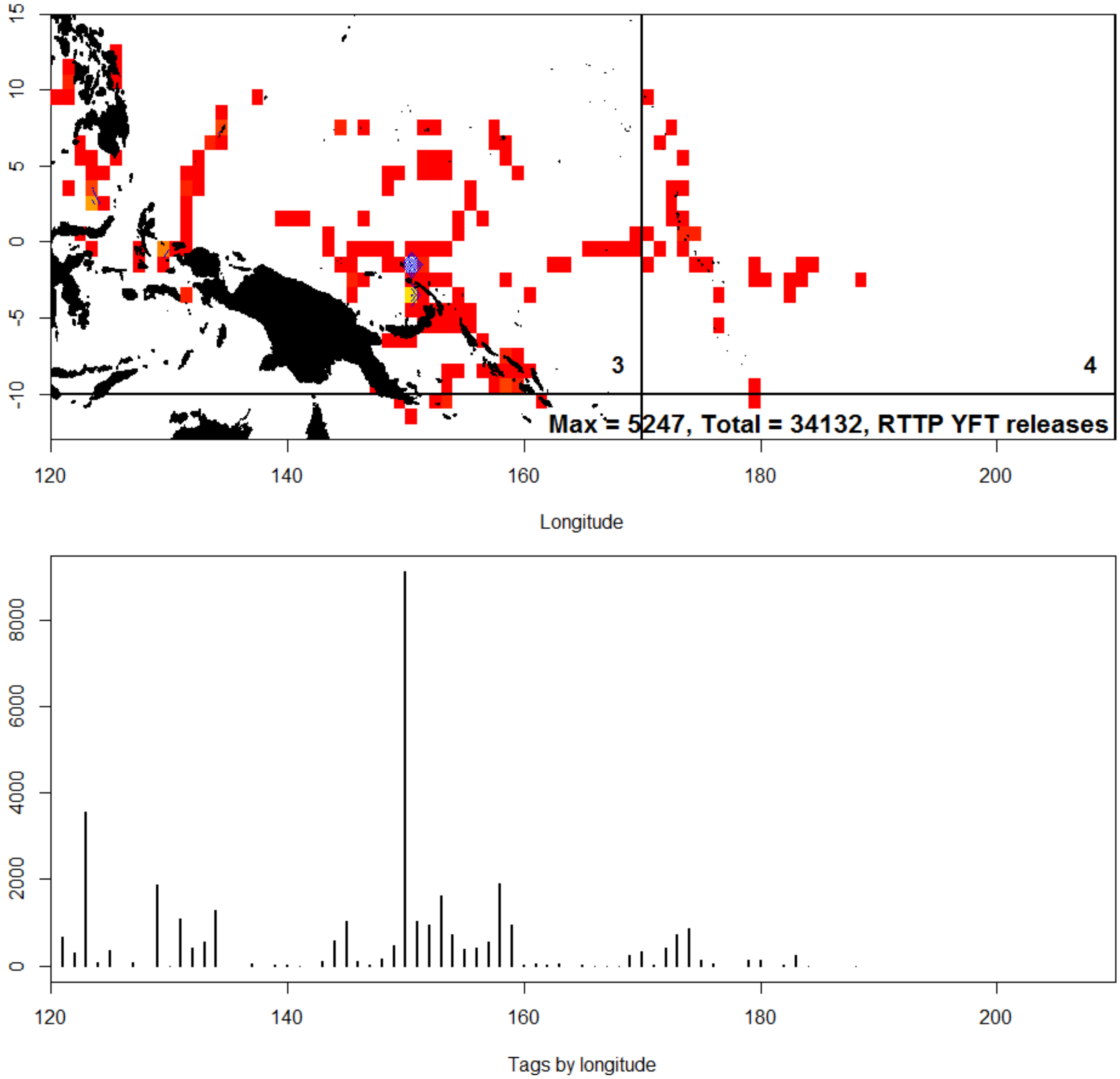


Figure 31: Tag release density map by 1 degree square for yellowfin tuna during the RTTP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude.

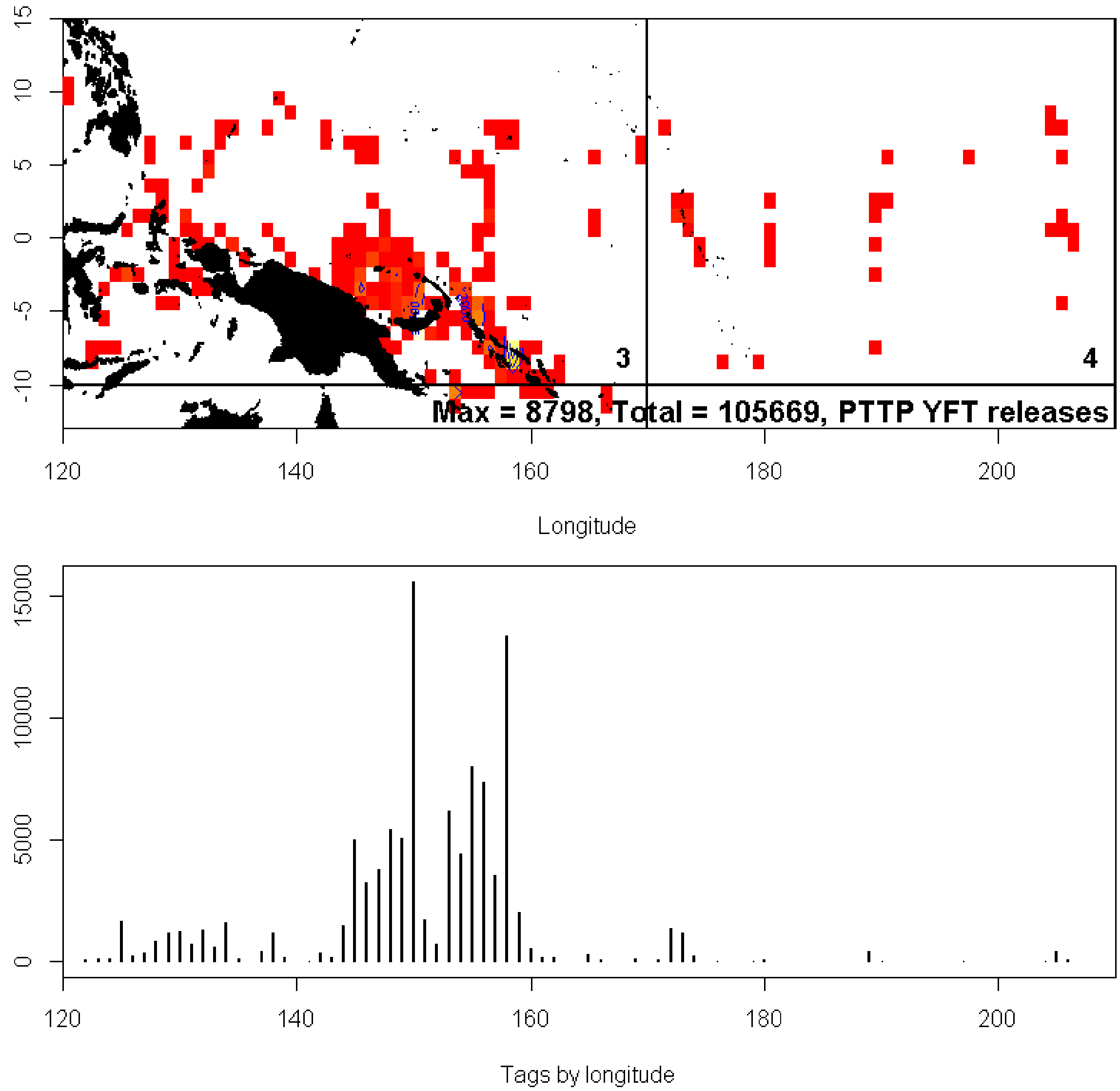


Figure 32: Tag release density map by 1 degree square for yellowfin tuna during the PTTP. Yellow indicates higher density. 'Max' is the number of releases in the 1 degree square with the most releases during the tagging programme, and 'Total' is the overall number of releases. The bar plot indicates the number of releases by longitude.

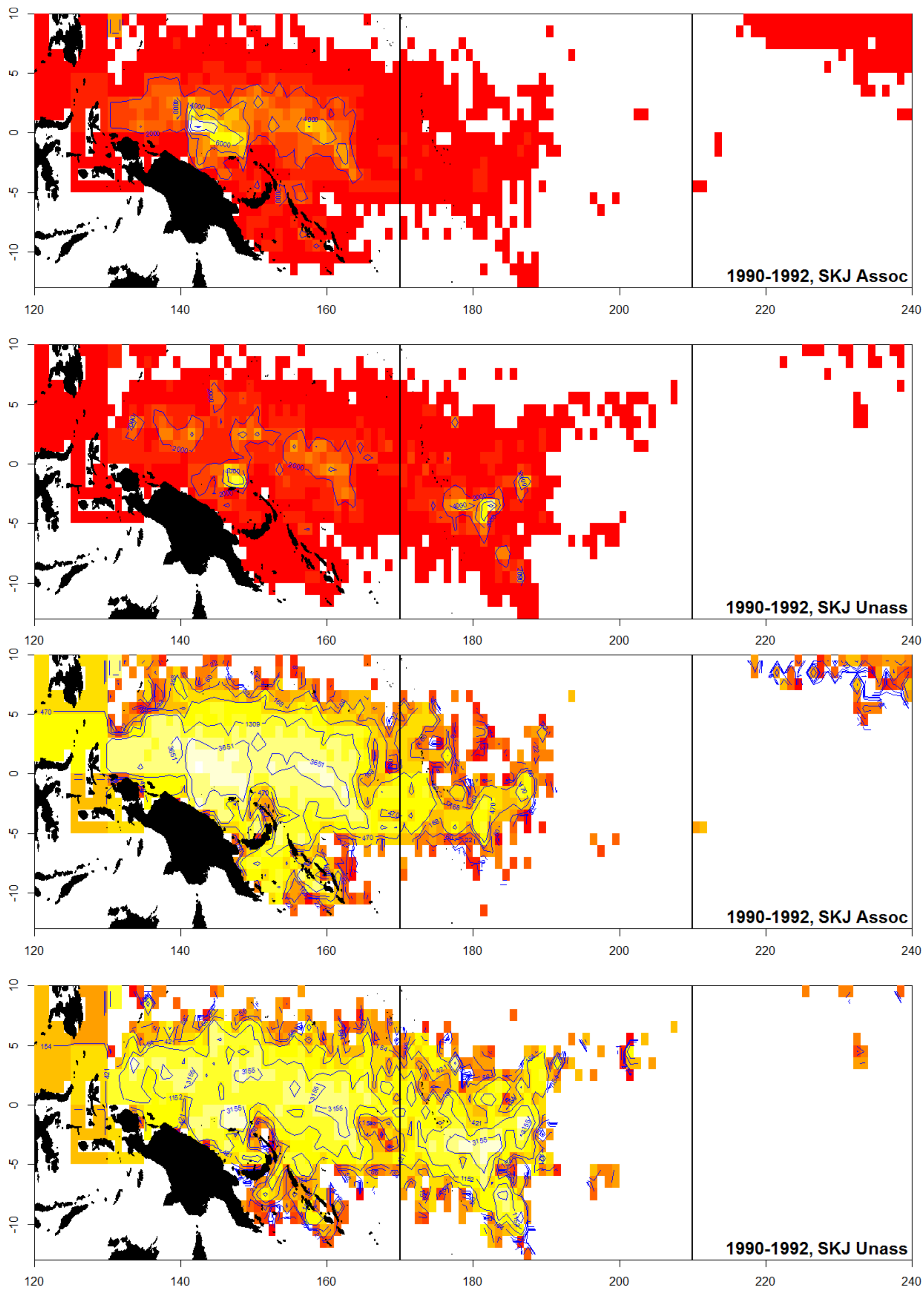


Figure 33: RTTP skipjack purse seine catch distribution maps by 1 degree square, by association type, and plotted on nominal (above) and log (below) scales. Associated and unassociated sets are on the same colour scale but with their own contour intervals. Yellow indicates higher catch. Units are metric tonnes per 1 degree square summed across years.

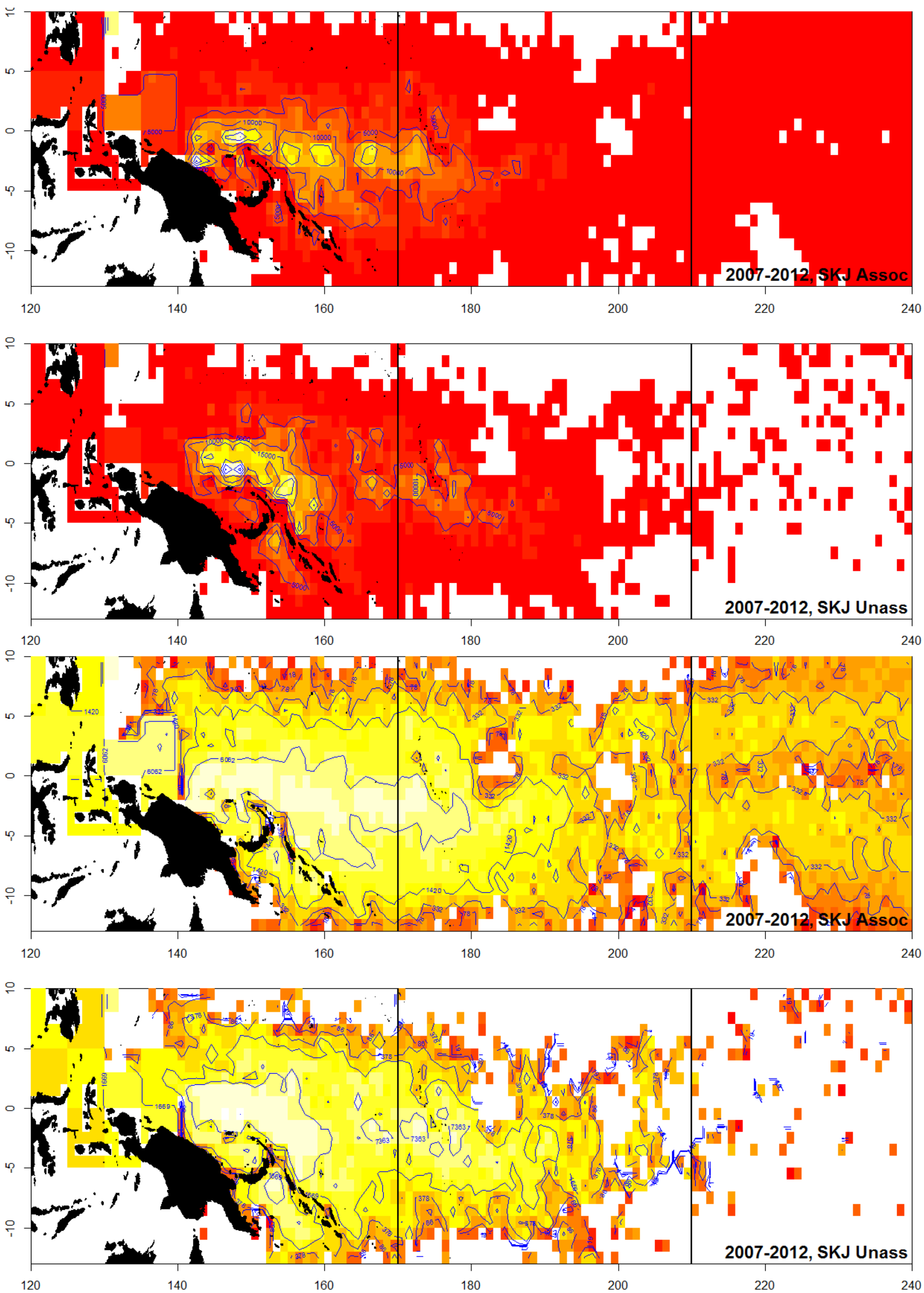


Figure 34: PTTP skipjack purse seine catch distribution maps by 1 degree square, by association type, and plotted on nominal (above) and log (below) scales. Associated and unassociated sets are on the same colour scale but with their own contour intervals. Yellow indicates higher catch. Units are metric tonnes per 1 degree square summed across years.

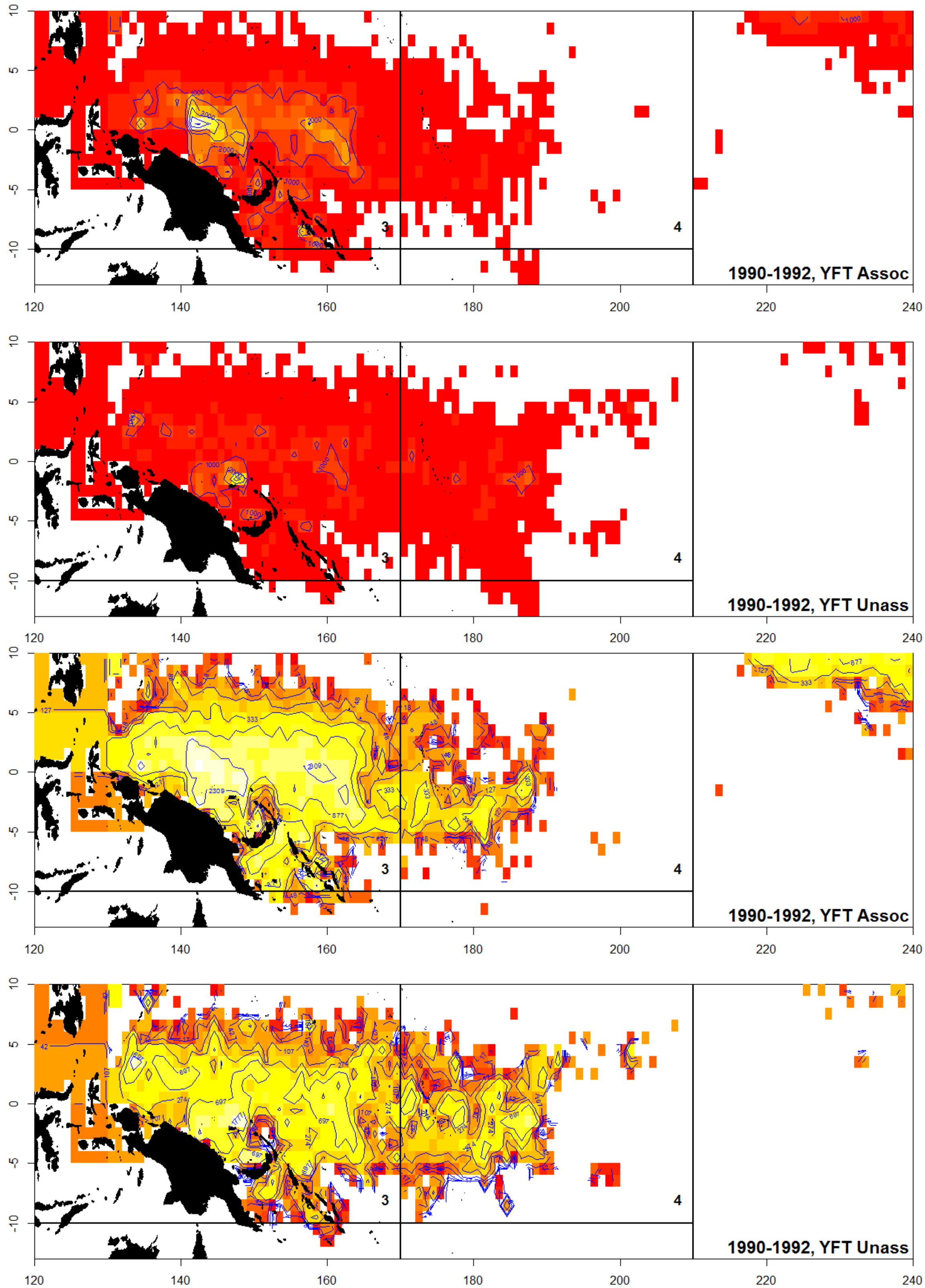


Figure 35: RTTP yellowfin purse seine catch distribution maps by 1 degree square, by association type, and plotted on nominal (above) and log (below) scales. Associated and unassociated sets are on the same colour scale but with their own contour intervals. Yellow indicates higher catch. Units are metric tonnes per 1 degree square summed across years.

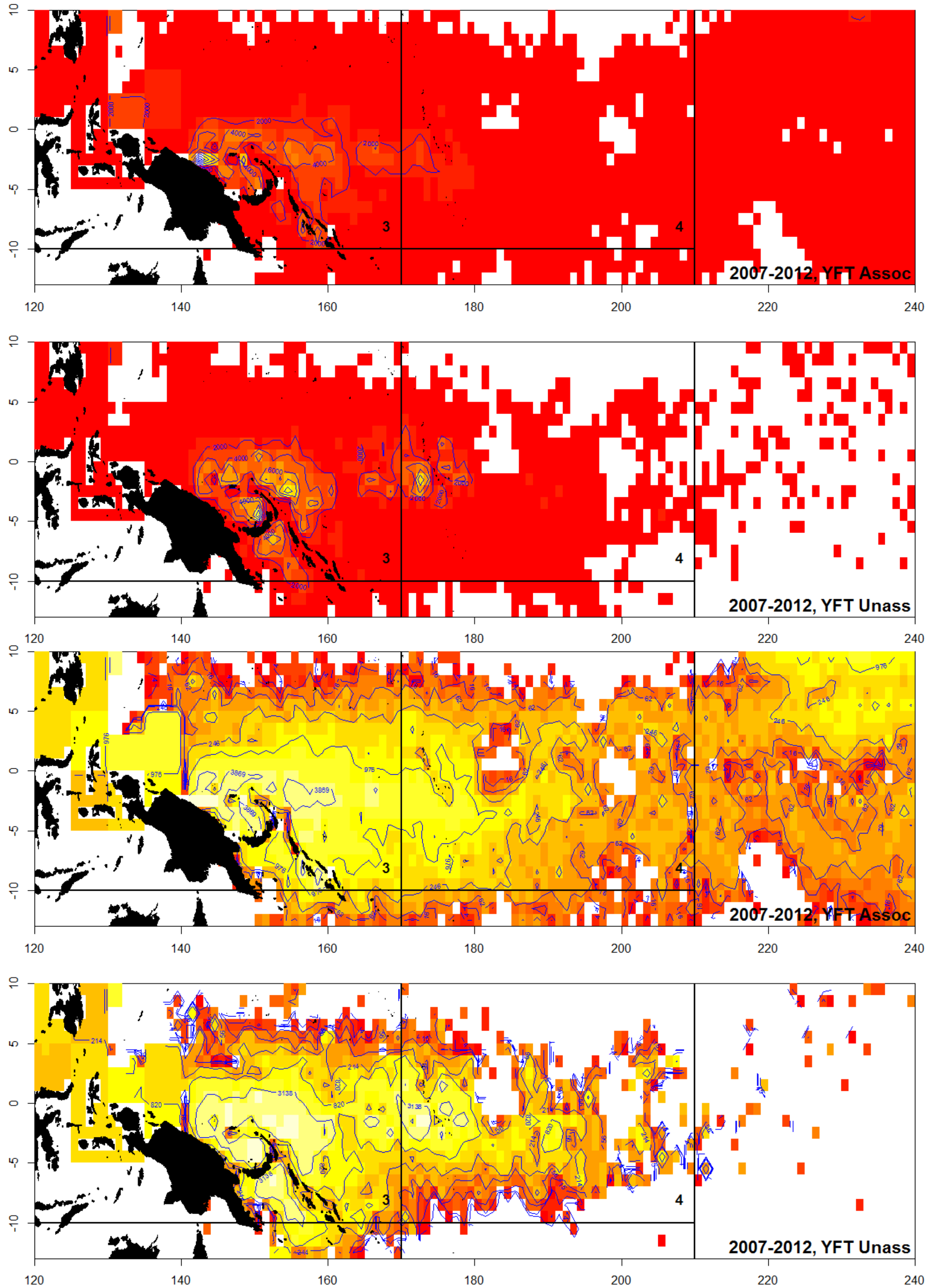


Figure 36: PTTP yellowfin purse seine catch distribution maps by 1 degree square, by association type, and plotted on nominal (above) and log (below) scales. Associated and unassociated sets are on the same colour scale but with their own contour intervals. Yellow indicates higher catch. Units are metric tonnes per 1 degree square summed across years.

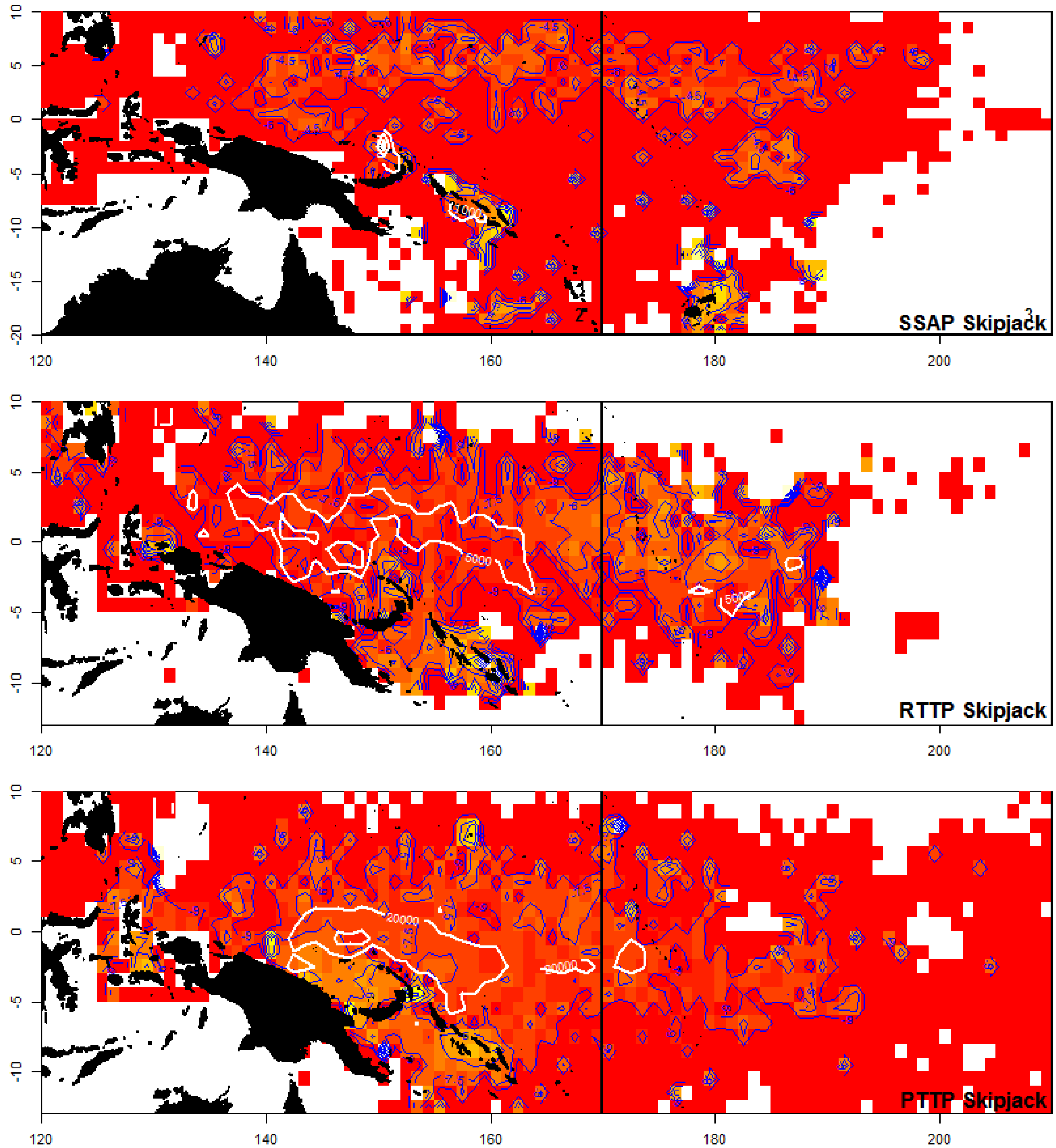


Figure 37: Tag recovery density map per 1 degree square for skipjack in the SSAP (top), RTTP (middle) and PTTP (bottom), for tags recovered after > 91 days (the mixing period). Yellow indicates higher tag density, and responses are on the log scale, so that density increases by a multiple of 4.5 with each blue contour line. The white contour lines indicate the areas of greatest purse seine catch.

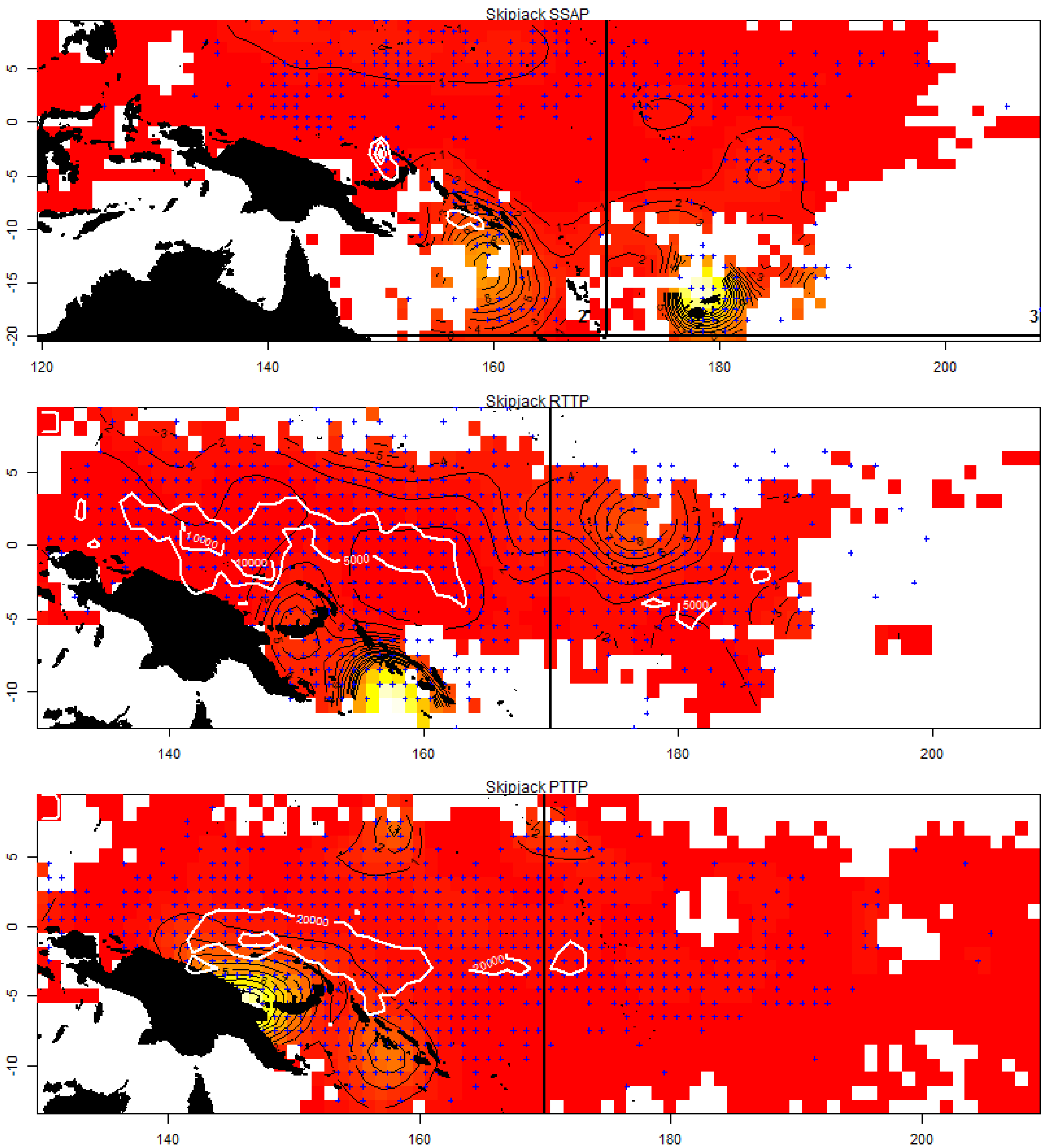


Figure 38: Predicted distribution of tags returned after the mixing period per unit of skipjack purse seine catch by 1 degree square, plotted on the nominal scale, as estimated by gam analyses. The black contour intervals are at units of 1 tag per x tonnes. The white contours indicate where the highest catches occur. The blue crosses indicate grid squares from which tags were returned. RTTP is above and PTTP below.

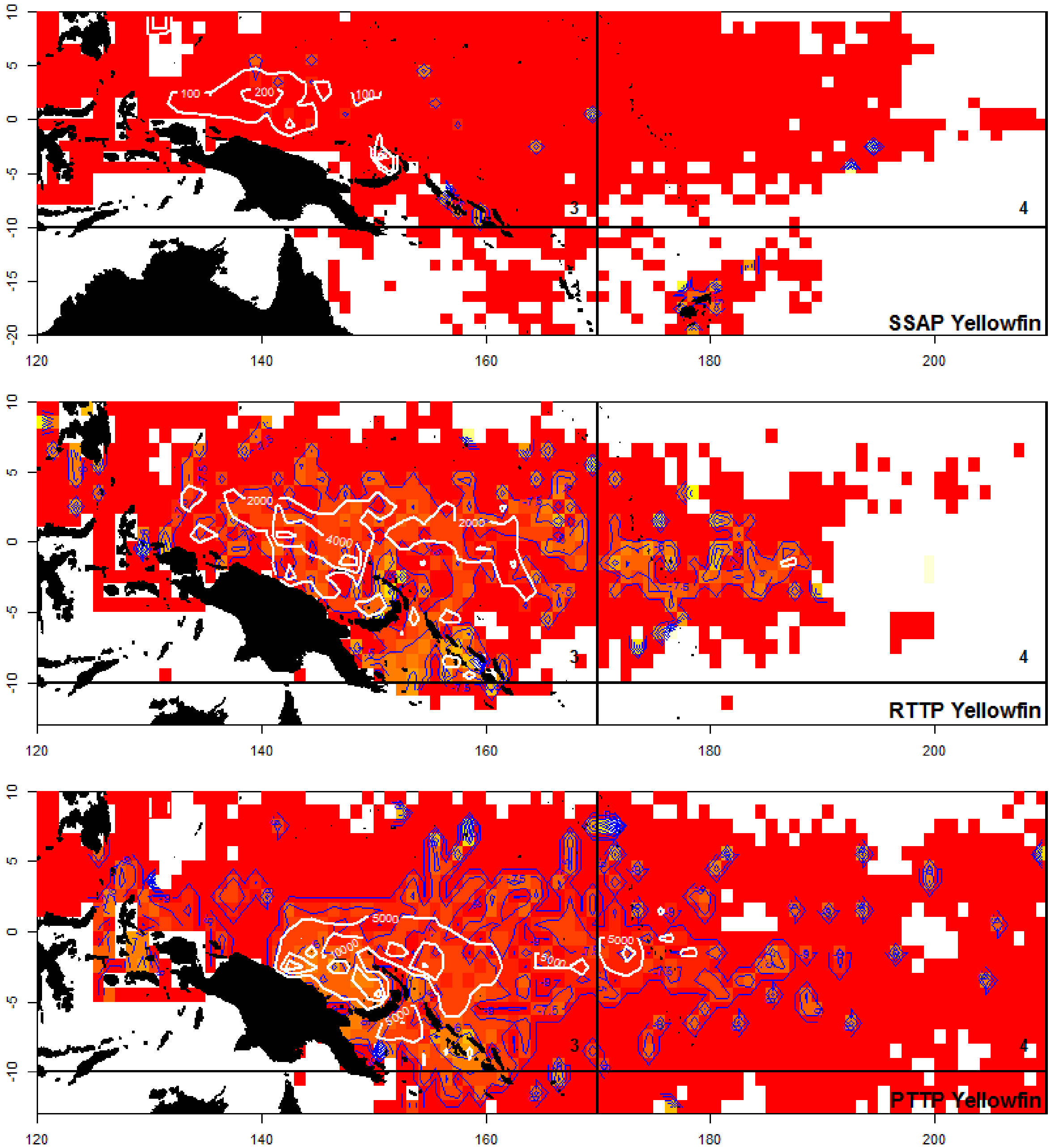


Figure 39: Tag recovery density map per 1 degree square for yellowfin in the SSAP (top), RTTP (middle) and PTTP (bottom), for tags recovered after > 183 days (the mixing period). Yellow indicates higher tag density, and responses are on the log scale, so that density increases by a multiple of 4.5 with each blue contour line. The white contour lines indicate the areas of greatest purse seine catch.

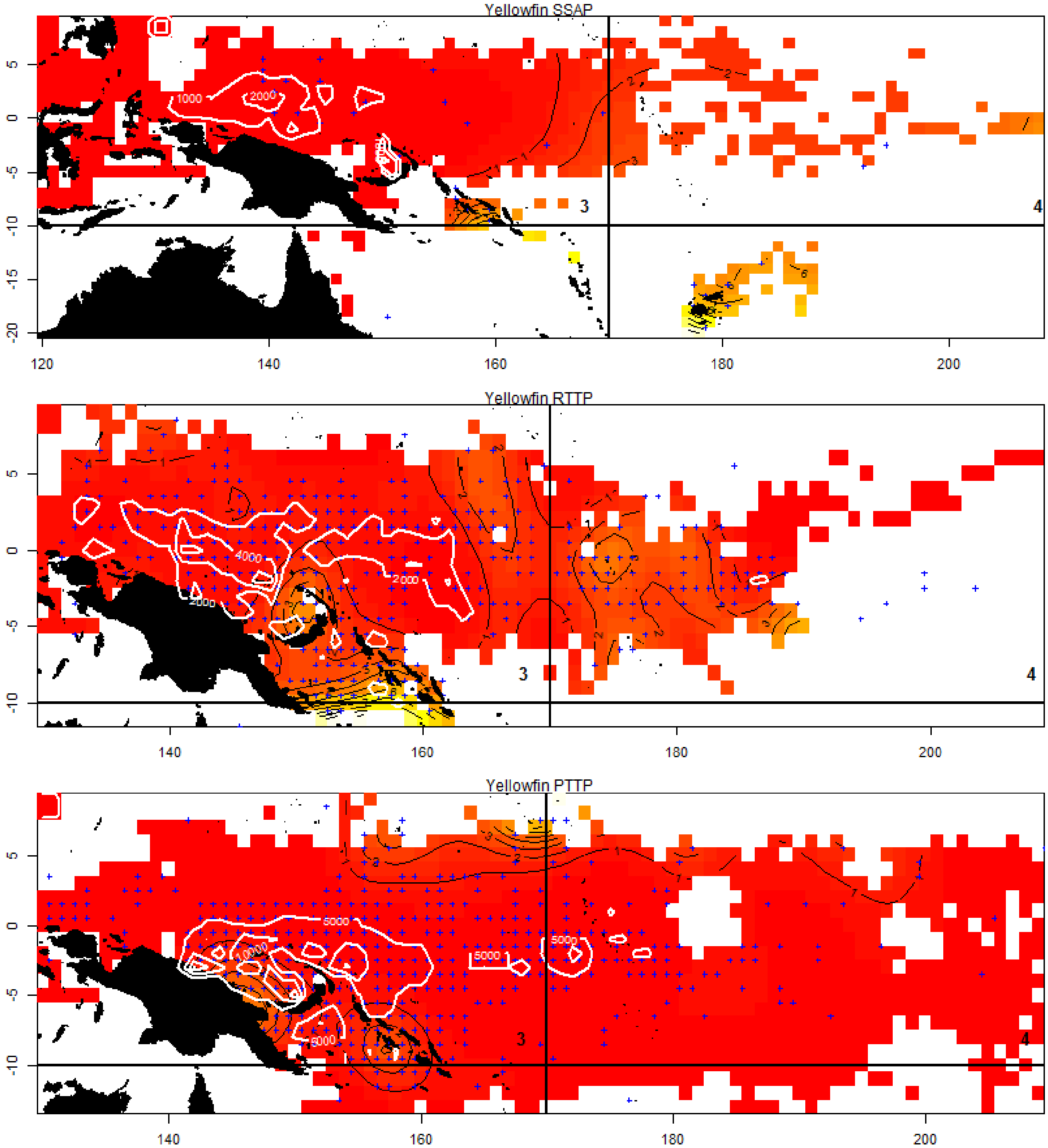


Figure 40: Predicted distribution of tags returned after the mixing period per unit of yellowfin purse seine catch by 1 degree square, plotted on the nominal scale, as estimated by gam analyses. The black contour intervals are at units of 1 tag per x tonnes. The white contours indicate where the highest catches occur. The blue crosses indicate grid squares from which tags were returned. RTTP is above and PTTP below.

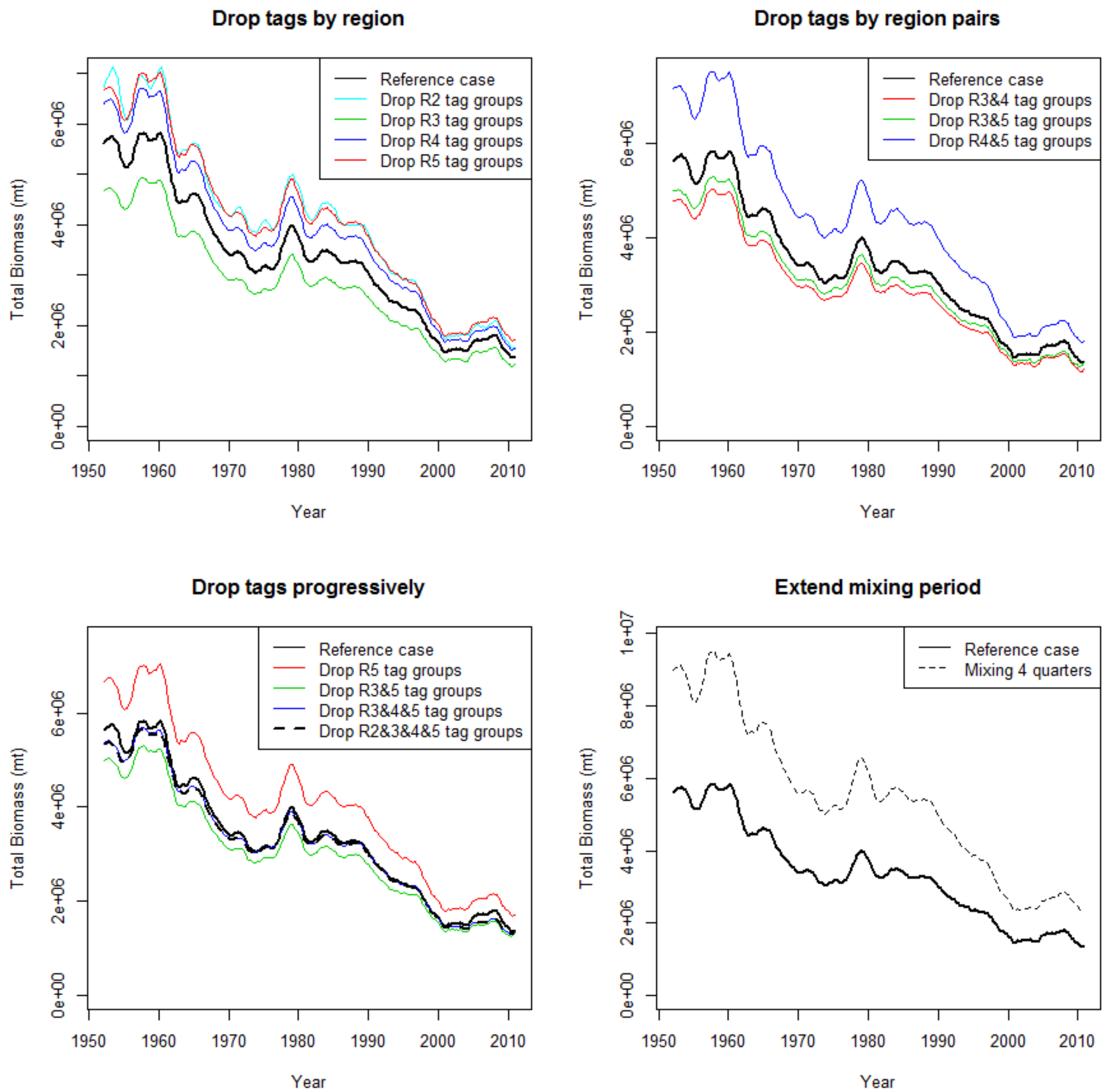


Figure 41: Yellowfin tuna total biomass by region estimated in the reference case of the 2011 yellowfin assessment (black) versus dropping tags from one or more regions (first three panels) or extending the mixing period from 2 quarters to 4 quarters (bottom right panel).