SCIENTIFIC COMMITTEE
SIXTEENTH REGULAR SESSION

ELECTRONIC MEETING
11-20 August 2020

Preliminary analysis and simulation of tag mixing and it's implication on the assessment of WCPO skipjack tuna

WCPFC-SC16-2020/SA-IP-10

J. Scutt Phillips[1], I. Senina[2], E. van Sebille[3], A. Sen Gupta[4], T Peatman[5] & S. Nicol[1]

[1] Oceanic Fisheries Programme (OFP), *The Pacific Community, Noumea, New Caledonia*
[2] Marine Ecosystems Modelling, Sustainable Fisheries Management Division, *CLS. 11 rue Hermes, 31520 Ramonville, France*
[3] Institute for Marine and Atmospheric Research, *Utrecht University, Utrecht, Netherlands*
[4] Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, *University of New South Wales, Sydney, Australia*
[5] Independent Fisheries Consultant, *Wiltshire, United Kingdom*

1 Executive summary

This Information Paper applies an individual-based model (Ikamoana, Scutt Phillips et al. 2018) to understand the impact that spatial scale, location and differing oceanographic conditions may have on mixing assumptions for skipjack tuna tagged in the WCPO.

Virtual tag releases for two archipelagic tag release locations in Papua New Guinea and an oceanic location in the Federated States of Micronesia were simulated under El Niño, La Niña and neutral ENSO phases. Tag mixing assumptions between tagged and untagged fish at 1, 2, 5, 10, 20 degree diameters around the tagging location, as well as at the associated MULTIFAN-CL assessment region were examined. Using Ikamoana to simulate the movement of 100,000 fish in each group through estimated, historical fields of fishing mortality, the probability of recapture was calculated for each individual fish. A simple metric based on the overlap in distribution of these recapture probabilities, a proxy for fishing pressure, was used to quantify the likelihood of mixing between the tagged fish and the differing groups of untagged fish.

Simulations predicted consistently higher recapture probabilities for tag releases within the Bismarck Sea than other release locations, during both El Niño and ENSO-neutral phases. Thus, these results indicate that current tag mixing assumptions for recapture are unlikely to be met for both the PNG releases, due to their proximity to areas of higher fishing pressure. A revision of the southern boundary of SKJ region 6 to the southern extent of the Solomon Sea (approx. 10 degrees south) would mitigate this issue and mixing may be achieved within 60 days or less for Bismarck Sea releases, a third shorter than the currently assumed period within the assessment.

Simulations of the expected recapture probability for the oceanic FSM tag releases reflected the distribution of fishing effort under the differing ENSO phases. Mixing-periods of between 30 and 270 days appear to apply the FSM release location, depending on ENSO phase. During La Niña conditions, very similar recapture probabilities were estimated between all tagging locations, as both tagged fish and fishing effort were compressed into similar areas along the edge of the cold tongue.

The IBM approach applied in this Information Paper could be further expanded to simulate all historical tag releases, identifying event-specific mixing periods with which to pre-filter data prior to incorporation into assessments. This would provide a tool to ensure optimal use of tags in MULTIFAN-CL models and assist with appropriate regional boundary definitions. Similarly, the approach could be applied to evaluate the movement-related assumptions of tagging analyses.

The SC is invited to note the following recommendations:

- There is a need to further examine mixing assumptions given their significant potential sensitivity to oceanographic conditions, fishing effort, and tuna behaviour
- The individual-based tagging simulator used here provides a pragmatic framework for examining mixing assumptions and the generation of artificial tagging data
- While true mixing is unlikely to occur for some historical tag releases within the currently assumed 1 quarter mixing period, mixing may occur faster than is currently assumed in some cases, or if model regional boundary changes were made. This would allow incorporation of more tagging data into MULTIFAN-CL stock assessment.

1. Introduction

An objective of the Pacific Tuna Tagging Programme (PTTP) is to tag a representative subset of the population in a region, of which the number, length composition and capture locations are known. This tagged group is then sampled via recaptures of tagged fish, and properties of the population can then be inferred including size distribution and rates of mortality, growth, and connectivity. This can then inform stock assessments and management decisions. Such tag-return models require that the tagged subset is representative of the underlying population in a region (Pine et al. 2003). For this to be the case, these models generally assume that after some period of time the tagged fish have mixed with the untagged population, to a degree that they are both subject to the same processes and probability of capture by the fishing operations in the region.

The capture of tagged fish may occur soon after tagging and consequently the time-period required to meet the assumption of complete mixing directly impacts the number of tags that are included for integration into MULTIFAN-CL stock assessment models. Rapid mixing of the tagged and untagged population would imply a greater number of tagged fish available for recapture which should provide better estimates of population characteristics. However in practice this mixing is likely to take some time. Attempts to quantify the degree to which complete mixing of the tagged and untagged populations takes place have generally concluded that the process is likely to be highly variable (Kolody & Hoyle 2013; Sippel et al. 2014). The analyses of Kolody and Hoyle (2013) noted that the time to complete mixing may vary by species, location and potentially oceanographic conditions.

The inclusion of tag recaptures that occur prior to complete mixing in MULTIFAN-CL stock assessment models can lead to significant bias in estimates of mortalities and movement. The current approach in MULTIFAN-CL stock assessment models is to apply a global mixing period, which in the current diagnostic skipjack tuna assessment is three months (one quarter). However, this may result in scenarios where for some locations the tagging data is over-penalised (i.e. more tag recaptures are removed than necessary). In this Information Paper we apply an individual-based model (IBM), using the conditional pathways experienced by virtually tagged fish to compare to those of the untagged population to understand the impact that spatial scale, location and differing oceanographic conditions may have on mixing assumptions for skipjack tuna in the WCPO. The improved understanding of the influence of these factors should lead to a more optimal use of the available tagging data in future skipjack assessments.

2. Methods

1.1 Movement model

To trace the fishing mortality experienced by simulated schools of skipjack tuna through time, we used the Ikamoana model (Scutt Phillips et al. 2018) to simulate the movement of both tagged and untagged fish. Ikamoana simulates the movement through discretised time and continuous space of particles representing either individual animals or groups of animals.

At each model time-step within Ikamoana, each individual fish is capable of sampling the fields affecting it, interpolated to that individual's current location. These fields may represent physical ocean currents (advection), habitat fields that depend on factors like temperature, oxygen and forage availability that drive both non-directional movements (kinesis) or directed movements (taxis), or any other fields that might affect the individual such as fishing pressure, uptake of chemicals or foraging success. The movement model used here is the Lagrangian formulation of the SEAPODYM movement model for young and adult fish, described fully in Scutt Phillips et al. (2018). For this application, we used parameters estimated from the most recent SEAPODYM solution for skipjack tuna integrating both fisheries and tagging data (Senina et al. 2020).

The Ikamoana simulation was forced with ocean current and habitat fields generated at ¼° grid resolution each week from the Mercator-Ocean global eddy-permitting NEMO ocean general circulation model, in the ORCA025 configuration under project GLORYS. Over a model domain between 100°E to 80°W and 50°S to 60°N, a large number of virtual skipjack tuna were released, aged 42.5 weeks, representing fish of fork length (FL) 39.98cm. This corresponds to the mean FL of tagged skipjack tuna in the Papua New Guinea and Solomon Islands region (assessment region 6). Fish age at the end of each week, and displacements due to advection, kinesis and taxis are calculated each day.

For each simulation, individual fish were released into the model domain using a variety of initial distributions at increasingly large scales. Initial distributions for untagged fish were obtained by random locating tuna in proportion to the density of skipjack tuna, at our chosen tagging age and release date, simulated by the SEAPODYM model. In this way the spatial distribution of tuna in SEAPODYM and Ikamoana should be equivalent if large numbers of fish are released. In the case of tagged fish, the starting point was a single point corresponding to one of three tagging locations (see below *Tagging Simulation Experiments*).

1.2 Mortality

Parameters estimating both natural and fishing mortality in the model are taken from the same SEAPODYM solution for skipjack tuna used to drive the movement model.

Natural mortality, *M*, is an age-dependent equation, with negligible spatial variation in this parameter solution (see Senina et al. 2020 for details).

Fishing mortality is exerted on a population by 14 fisheries operating in the Pacific Ocean and comprise almost exclusively of purse seine and pole-and-line gears. Catch and effort data provided by SPC is spatially aggregated to between 1° and 5° resolution across fleets and used to estimate parameters in SEAPODYM (Senina et al. 2020). A 15th fishery, compromising of Indonesian and Philippines purse seine vessels, was not considered in these simulations because these fleets typically operate west of 150°E, and result in estimated mortality parameters within SEAPODYM that are highly unrealistic, and thus within SEAPODYM simulations fish are depleted by the observed catch for these fisheries rather than by the estimated fishing mortality. However, as this study aims to quantify the probability of capture for individual fish, we cannot use this approach of cell-based biomass depletion, and so at present these fisheries are simply removed from the calculation of fishing mortality fields.

Spatially and temporally varying fields of fishing mortality, *F*, were calculated at the same temporal resolution as the simulated tuna age classes. *F* is given by:

$$F_{f,j} = q_f E_{f,j} S_l \tag{1}$$

Where *F* of fishery *f* in location *j* is the product of the catchability coefficient of that fishery *q*, the corresponding fishing effort *E* at location *j*, and an at-age length *l* dependent selectivity of each separate fishery S_l. For this study skipjack tuna age classes are weekly, and thus *F* varied temporally at this same rate. Parameters and selectivity equations are defined in Senina et al. (2020).

The equations describing F and M provide a proportional mortality due to natural causes or fishing, i.e. that for a given cell and time-step, that proportion of the biomass present will be lost to these processes. In reality, the vulnerability to this mortality of the individual fish within a cell will depend on factors such as whether the fish is associating with a floating object, their vertical movements, and the distribution of schools in the immediate area, all of which are not yet modelled in SEAPODYM.

In our individual-based framework, for simplicity we assume that within each ¼ cell of spatially defined mortality, the probability that an individual fish is caught, or dies due to natural causes, is uniform across all the individuals present in that cell. Therefore, the total reduction in biomass at each cell over a time step Δt, emerges from each individual fish dying or being caught with probability $P(nat)_t$ or $P(catch)_t$ equal to the M_t or F_t of that cell, respectively, at time t. Individual particles are never removed from the simulation, rather the probability of the fish dying due to either process is recorded along each unique pathway of all particles. The total number of simulated fish in the model domain, N, is the sum of the probabilities of survival by time t for all simulated particles (n=X), $P(surv)_t$. We examine metrics associated with these densities and probabilities for each separate tagging scenario (see below).

$$P(mor)_t = \left(1 - e^{-(M_t+F_t)\Delta t}\right)P(surv)_t$$

$$P(surv)_t = \prod_{n=0}^{t-1} 1 - P(mor)_n \qquad (2)$$

$$P(nat)_t = \frac{M_t}{M_t + F_t}P(mor)_t$$

$$P(catch)_t = \frac{F_t}{M_t + F_t}P(mor)_t \qquad (3)$$

$$N(t) = \sum_{i=1}^{X} P(surv)_{t,i}$$

1.3 Tagging Simulation Experiments

To examine the degree to which different tagging scenarios may result in tagged fish experiencing the fishing mortality experienced by the untagged population, a suite of 9-month Ikamoana simulations were run. Simulations were run for tag releases at three contrasting locations, and during three separate years of differing ENSO phase.

For each scenario, several separate simulations were run. First, for each tag release location, 100,000 fish were released at a single point location and left to disperse over the course of the simulation. Then, simulations of 100,000 untagged fish of the same cohort were undertaken as the baseline 'truth' with which to make comparisons to the tagged fish released in different locations. These untagged fish were initiated within an area of increasing radius from the tagging location, as well as within the entire stock assessment region containing the tagging location. The distribution of tagged fish within the area is proportional to density provided by the SEAPODYM simulation for fish of this size (see *movement model* above). We used tag release locations that approximated three areas of large historical release events of the PTTP in the EEZs of Papua New Guinea (Bismarck Sea PNG and Solomon Sea SOL releases) and the Federated States of Micronesia (FSM). These tag releases locations are summarised in table 1, and the spatial positions of releases and increasing radius areas of untagged fish in figure 1.

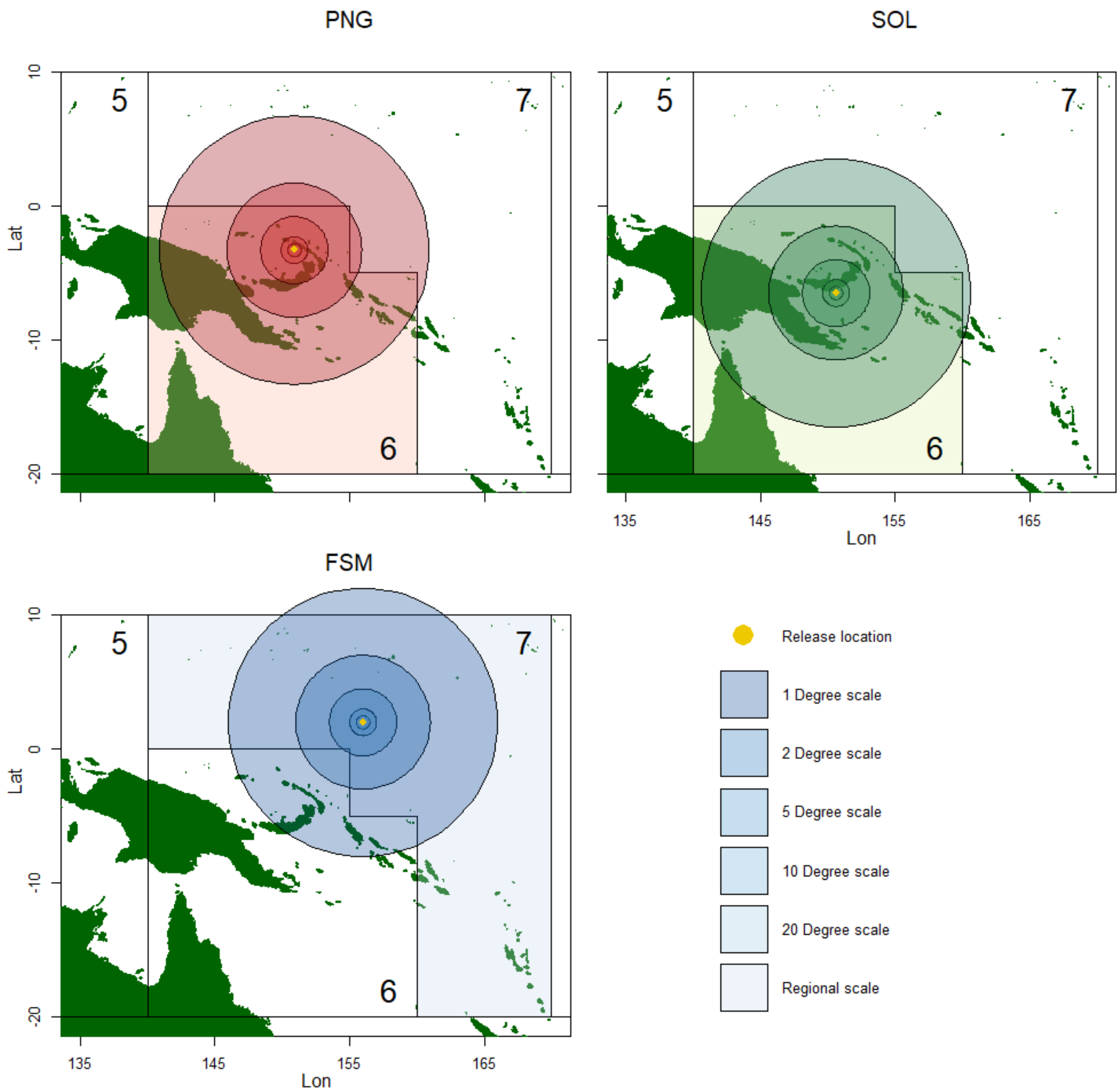

Figure 1. Simulated tagged fish release locations and areas of untagged fish releases over increasingly large scales for the three release scenarios.

Table 1. Summary of tag release locations used in simulation experiments

Name	EEZ	Longitude	Latitude	Skipjack Assessment Region
PNG	Papua New Guinea	150° 54' 0" E	3° 17' 60" S	6
SOL	Papua New Guinea	150° 35' 60" E	6° 30' 0" S	6
FSM	Federated States of Micronesia	156° 0' 0" E	2° 0' 0" N	7

In addition to these tag release locations, simulations were run beginning at different times to examine the effect of ENSO-driven oceanographic effects on the simulated dispersion of both tagged and untagged fish. We ran paired untagged cohort/tag release simulations for release scenarios during mid-March during 2012 (a period of ENSO-neutral ocean conditions), 2010 (leading into two years of moderate La Niña conditions), and 2015 (leading into a strong El Niño event).

All simulated fish trajectories recorded the probability of capture (equation 3), as well as the fishing mortality F, overall probability of survival (equation 2) and lon/lat position at each daily time-step (Δt). For each fish, the probability of capture is a function of its unique trajectory through the spatiotemporally varying fields of fishing mortality, and temporally varying natural mortality. The recapture probability necessarily increases through time as consecutive time-steps result in greater chance of mortality through either natural mortality or fishing, and will asymptote at the limit when further fishing mortality experienced will result in negligible increases (figure 2).

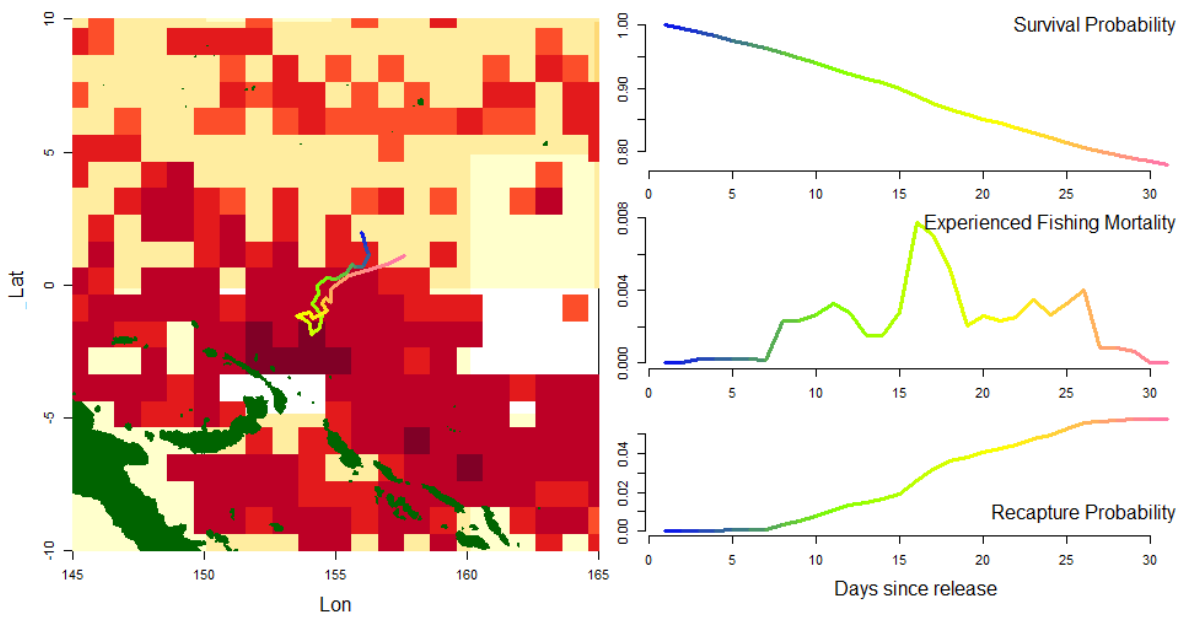

Figure 2. Left: An example trajectory of a single simulated fish over 30 days following release, with spatially-varying fishing mortality for the period shown underneath (low to high F coloured white to red). Right: From top to bottom, the corresponding probability of survival (equation 2), experienced fishing mortality (proportion per day), and probability of recapture (equation 3) experienced over the trajectory.

1.4 Analysis of mixing

The aim of the simulation experiments were to quantify the degree to which simulated fish released at the tag locations experienced the same fishing mortality as a simulated, untagged cohort of the same age. The probability of capture along each fish' trajectory was used as the basis for metrics describing this mixing, with the spatial extent of mixing examined for each scenario by comparing the tagged fish to groups of the untagged cohort at increasingly large spatial scales. These groups represented all untagged fish within a 1°, 2°, 5°, 10° and 20° diameter circle around the tagging location, as well as the assessment region in which that tagging location was located.

These assessment regions vary in size, and were taken from the most recent stock assessment for skipjack tuna (Vincent et al. 2019), and are the spatial scale at which complete mixing is assumed to occur after three months from any given tagging location within the region bounds.

For both the tagged and untagged fish in each scenario, the distribution in probability of capture after time *t* (equation 3) for all individuals was calculated and compared. Similarly, the spatial differences in trajectories and emergent distribution was examined to understand why experienced recapture probabilities between the different groups may be different.

2 Results

Brief overviews of dispersion and fishing pressure are given here, with full results presented in Appendix A. Levels of tax mixing are then summarised below for key scenarios and time periods.

2.1 Dispersion

Dispersion patterns of tagged and untagged groups of fish varied in response to ENSO phases, being particularly affected during La Nina years. Patterns in the movement of untagged fish at larger spatial scales around the two tagging locations in Papua New Guinea were consistent across all scenarios, with a division between fish distributed in the southern area towards the Torres Straight and Coral Sea, and more coastal movement in the Bismarck Sea and west towards Indonesia. The dispersion of both tagged and untagged groups of fish at and around the FSM tagging location demonstrated differing, eastern, western and diffusive patterns dependant on the ENSO phase.

Maps of dispersion and full description of these results are given in Appendix A.

2.2 Fishing pressure

To demonstrate the variability in fishing pressure experienced by tagged and untagged groups of simulated fish across our scenarios, the distribution of probability of capture by time *t* (equation 3) was plotted for all fish in each group at monthly increments (figure 4).

For the ENSO-neutral 2012 reference scenario, the median probability of recapture increased rapidly for both PNG and SOL tagged fish during the first 90 days at liberty. This increase began to asymptote for SOL tagged fish, but continued for the PNG release until 150 days at liberty, before levelling off. In contrast, the FSM tagging release experienced much lower fishing pressure until 150 days at liberty, at which point a larger number of tagged individuals had moved into areas of high fishing pressure and the distribution widened. By the end of the 270 day simulation, PNG tagged individuals had a median probability of capture of 0.14 (interquartile range, IQR = 0.09), with a slight positive skew. This value was 0.07 (IQR = 0.12) for SOL tagged fish, with a near normal distribution, and was 0.06 (IQR = 0.09) for FSM tagged fish with positive skewed distribution.

For untagged fish groups over increasing areas around the release location, these distributions were very similar up to 5-degrees around the tagging location for the PNG and SOL releases, even after 60 days. For FSM scenarios, this was only the case up to 2-degrees. In these cases, the distribution of experienced fishing pressure for untagged fish over larger areas rapidly departed from the tagged fish group from the beginning of the scenario. This was not the case, however, for untagged fish at the scale of the actual assessment region of the FSM release, which experienced a fishing pressure very similar to the tagged release group from 30 days onwards, albeit with a lower median and greater variation in probability of capture. In the case of the PNG and SOL scenarios, larger areas and the assessment regions of untagged fish were consistently and significantly under-depleted compared to their corresponding tag release groups, which experienced consistently greater fishing pressure.

Differences in experienced fishing pressure over time for the different tagged and untagged fish groups are fully described for all scenarios in Appendix A.

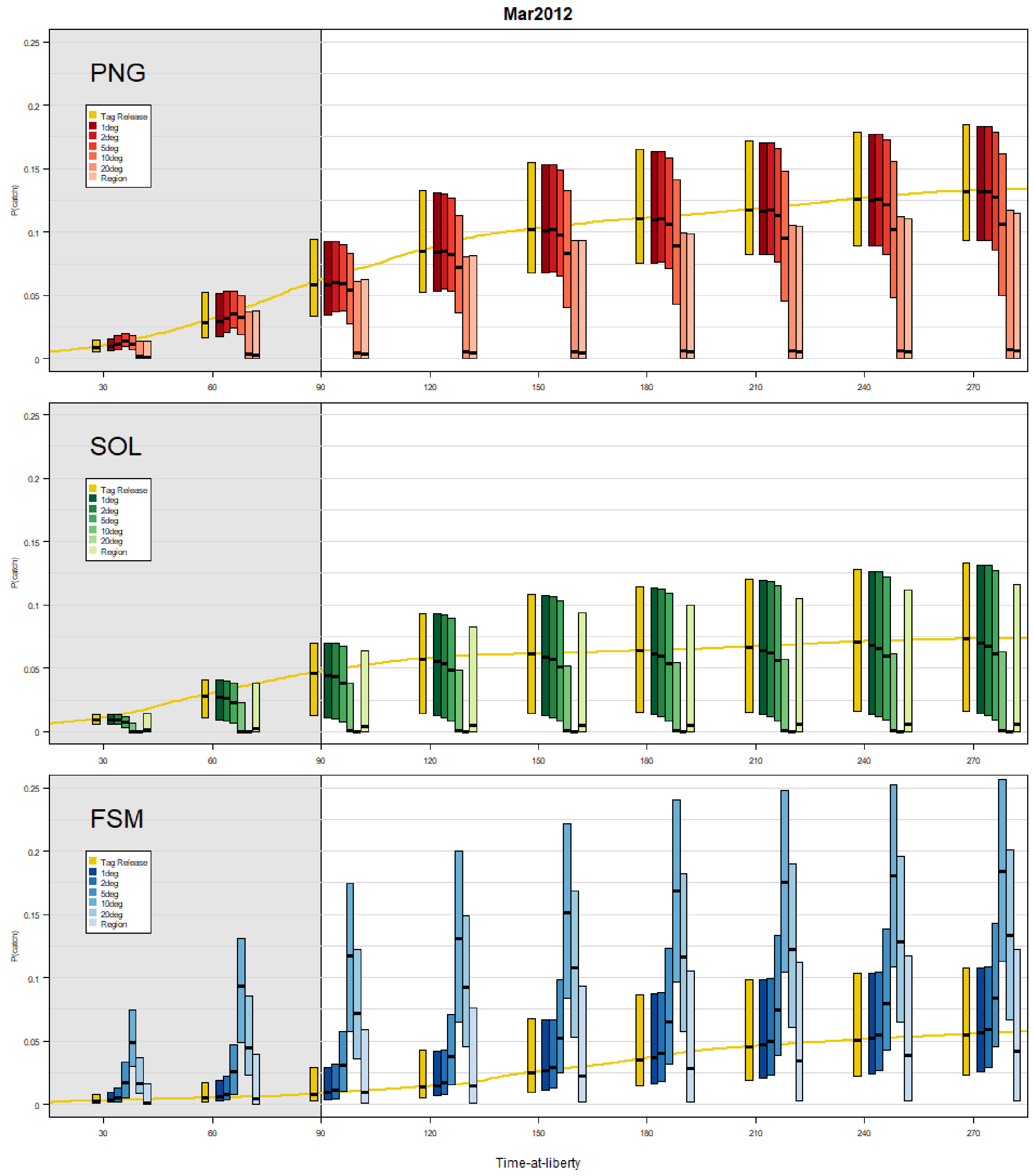

Figure 4. . Boxplots showing the median and interquartile ranges of recapture probability for tagged and all untagged fish groups through time for reference ENSO-neutral 2012 scenario. The median cumulative recapture probability of the tagged group is shown with a golden line, and the current, assumed mixing period for skipjack tuna indicated by the grey shaded area.

2.3 Tag Mixing

To summarise the degree of tag mixing across the many scenarios, temporal periods and differing groups of untagged fish, we used a simple metric to indicate that the distributions of recapture probabilities were similar between two groups (Table 2). If median recapture probability of both the tagged and untagged groups lay within the interquartile ranges of each other, we considered this indicative of potential mixing. After consideration of the full results (Figure 4, Appendix A.), we compared mixing of fish tagged at our three release locations with untagged fish at 5°, 10° and the stock assessment region, and after 1, 2, 3, and 9 months at liberty.

Assuming a 10° area of untagged fish around the tagging location, tagged fish at the Bismarck PNG area mixed after only 1 or 2 months for all three temporal scenarios, but were never mixed with the entire stock assessment region even after the full length of the 9-month simulation. Conversely, the Solomon Sea SOL release never mixed with the untagged fish groups considered in Table 2 at areas greater than a 5° diameter around the tagging location. Mixing varied most by ENSO phase for the oceanic FSM release, although mixing at the regional scale was always achieved by the end of the 9-month simulation, and as quickly as 1 month for the reference, ENSO-neutral scenario.

It is worth nothing that some of the unintuitive results, such as fish tagged at the oceanic FSM location not mixing at the smaller, 5° scale, yet mixing quickly at the larger regional scale, is due the circular area of untagged fish including areas outside of the stock assessment region corresponding to the tag release location (Figure 1). For example, a 10° area around this tagging location will include untagged fish close the Bismarck Sea area of the neighbouring region 6.

Table 2. Presence of mixing (green) and non-mixing (red) between tagged fish and untagged fish at 5°, 10° and stock assessment region scale, after 1, 2, 3 and 9 months. Table is separated by tagging location (left column) and ENSO period (first row). Appropriate mixing between a group of tagged and a group of untagged fish is defined here as the median recapture probability of all fish from each group lying within the interquartile range of recapture probability of the other group.

Location	El Nino (2015)											
Spatial Mixing Scale	5°				10°				Regional			
Months-at-liberty	1	2	3	9	1	2	3	9	1	2	3	9
Bismarck Sea (PNG)	green	green	green	green	green	green	green	green	red	red	red	red
Solomon Sea (SOL)	green	green	green	green	red	red	red	red	red	red	red	red
Oceanic (FSM)	red	red	red	red	red	red	red	red	red	green	green	green

Location	ENSO-neutral (2012)											
Spatial Mixing Scale	5°				10°				Regional			
Months-at-liberty	1	2	3	9	1	2	3	9	1	2	3	9
Bismarck Sea (PNG)	red	green	green	green	green	green	green	green	red	red	red	red
Solomon Sea (SOL)	green	green	green	green	red	red	red	red	red	red	red	red
Oceanic (FSM)	red	red	red	green	red	red	red	red	green	green	green	green

Location	La Nina (2010)											
Spatial Mixing Scale	5°				10°				Regional			
Months-at-liberty	1	2	3	9	1	2	3	9	1	2	3	9
Bismarck Sea (PNG)	red	green	green	green	red	green	green	green	red	red	red	red
Solomon Sea (SOL)	green	green	green	green	red	red	red	red	red	red	red	red
Oceanic (FSM)	red	red	green	green	red	red	red	green	red	red	red	green

3 Discussion

Incorporation of mark-recapture tagging data into stock assessment of WCPO tropical tunas has been a standard procedure for two decades (Hampton & Fournier 2001). Historical and ongoing tagging programmes in the region have been undertaken since the 70s as part of the Skipjack Survey and Assessment Programme, and the Regional and Pacific Tuna Tagging Programmes (SSAP, RTTP, PTTP). These data are recognised as a crucial component of assessment and monitoring, particularly in the case of skipjack tuna (Leroy et al. 2015), and are used under standard assumptions regarding tag mixing.

The simulation analyses undertaken here demonstrated the influence of location and oceanographic conditions on time to achieve complete mixing. Over the 270 days of simulation, mixing assumptions for fish capture were often satisfied at the 5-10° resolution for the tag release locations in the Bismarck Sea (PNG) for the ENSO phases tested, but never at the stock assessment region scale. In the case of the Solomon Sea release (SOL), mixing only ever occurred at the 5° area around the tagging location. For the oceanic (FSM) location however, comparable fish recapture probabilities were observed at the MULTIFAN-CL region scale as those reported for the tagged group, though the time for this mixing to occur varied by ENSO phase.

The simulations for the two locations in PNG (PNG, SOL) never demonstrated equivalent recapture probabilities at the 20 degree and MULTIFAN-CL region scale largely due to dispersion and occurrence of non-tagged individuals in locations south of the Solomon Sea. These areas experience low fishing pressure and are not known for high densities of skipjack, and so it is plausible that the underlying distribution and fish movement model overestimates presence and dispersion into these regions. A shift in the MULTIFAN-CL boundary for SKJ region 6 to the southern end of the Solomon Sea would most likely result in comparable fish recapture rates at this new regional scale. This adjustment would also indicate that a mixing period between 30-60 days since tag release could be potentially assumed, depending on the release location and ENSO phase. It is worth noting that we removed certain Indonesian and Philippines purse seine fisheries from the simulation, and since fish moved west towards these fisheries the recapture probabilities for fish tagged at the Papua New Guinea locations likely represent underestimates.

The interpretation of recapture probabilities for simulations of the FSM tag releases were consistent with distribution of fishing effort under the differing ENSO phases. During La Nina conditions the fish movement model disperses fish to predominantly westwards areas from the release site. Fishing effort in this period is also typically concentrated in this western region. The concentration of both tagged and untagged fish and fishing effort in this region results in greater occurrence of mixing across spatial scales for all tag release locations examined here . A mixing-period of 60 days or less could apply for Bismarck Sea (PNG) released fish with the shifted region 6 boundary described above, under these La Nina circumstances. While the recapture probabilities for the FSM release site varied with oceanographic conditions, they were comparable with untagged fish at the MULTIFAN-CL regional scale under each ENSO phase examined. A mixing-period between 30 - 60 days was apparent for FSM releases under neutral and El Nino conditions, respectively. Such a mixing period could allow a greater number of tags to be included in MULTIFAN-CL assessments from such tag releases.

In general, the_recapture probability varied under each tag release scenario, with the majority of fish experiencing a total probability of recapture that varied around 10% for the reference scenario and the full distribution range much further. Depending on the nature of school cohesion, this could explain the large observed variability in tag returns historically, particularly when tags are spread across relatively fewer schools of fish.

The IBM approach applied in this Information Paper could be similarly used to simulate all historical tag releases to identify event-specific mixing periods with which to pre-filter data prior to incorporation into MULTIFAN-CL . This would provide a tool to ensure the maximum use of tags in MULTIFAN-CL models and assist with more appropriate regional boundary definitions, given the distribution of tag release data. Similarly the approach could be applied to evaluate movement and alternative behavioural assumptions in the context of informing data-use in MULTIFAN-CL , as well as simulating data for operating models within Management Strategy Evaluation.

The SC is invited to note the following recommendations:

- There is a need to further examine mixing assumptions given their significant potential sensitivity to oceanographic conditions, fishing effort, and tuna behaviour
- The individual-based tagging simulator used here provides a pragmatic framework for examining mixing assumptions and the generation of artificial tagging data
- While true mixing is unlikely to occur for some historical tag releases within the currently assumed 1 quarter mixing period, mixing may occur faster than is currently assumed in some cases, or if model regional boundary changes were made. This would allow incorporation of more tagging data into MULTIFAN-CL stock assessment.

4 References

Hampton, J. & DA. Fournier. A spatially disaggregated, length-based, age-structured population model of yellowfin tuna (Thunnus albacares) in the western and central Pacific Ocean. *Marine and Freshwater Research* 52.7 (2001): 937-963.

Kolody, D. & Hoyle, S. Evaluation of tag mixing assumptions in western Pacific Ocean skipjack tuna stock assessment models. *Fish. Res.* (2013).

Leroy, B. *et al.* Lessons learned from implementing three, large-scale tuna tagging programmes in the western and central Pacific Ocean. *Fish. Res.* **163**, 23–33 (2015).

Pine, William E., et al. "A review of tagging methods for estimating fish population size and components of mortality. *Fisheries* 28.10 (2003): 10-23.

Scutt Phillips, J. *et al.* An individual-based model of skipjack tuna (Katsuwonus pelamis) movement in the tropical Pacific ocean. *Prog. Oceanogr.* **164**, 63–74 (2018).

Senina, I., Lehodey, P., Sibert, J. & Hampton, J. Integrating tagging and fisheries data into a spatial population dynamics model to improve its predictive skills. *Can. J. Fish. Aquat. Sci.* **77**, 576–593 (2020).

Sippel, T. *et al.* Using movement data from electronic tags in fisheries stock assessment: A review of models, technology and experimental design. *Fish. Res.* (2014).

5 Appendix A.

5.1 Dispersion Results

For the reference 2012 (ENSO-neutral) simulation, individual releases at the three tagging locations showed very different patterns of dispersion over the nine-months of simulated time at liberty (figure 3).

Simulated individuals released in the Bismarck PNG location remained largely in the coastal area of Papua New Guinea or moved west towards Indonesia. Individuals released south of New Britain at the Solomon Sea SOL location displayed a split distribution between a similar coastal Papua New Guinea movement towards Indonesia, and southerly movements towards the Coral Sea. For the oceanic FSM release, tagged fish dispersed more widely with a slight tendency for eastward movement around the equator.

When comparing to untagged fish at increasing spatial scales around each release location, patterns were more similar for the PNG and SOL release locations. Untagged individuals up to a 5-degree radius around the tag release location followed remarkably similarly dispersions to the tagged fish, for each location respectively. At 10-degrees and greater, however, the majority of the individuals were distributed around the south of the Papua New Guinea EEZ and the Coral Sea. For untagged fish around the FSM location, fish distributed in increasing areas around the tagging location dispersed further east and south of the equator than the tagged fish. Those that begun the simulation closer to the PNG release location, as the radius of the untagged group increased, naturally followed a similar dispersion pattern to simulations for that area. This was not the case, however, for the simulation of untagged fish at the assessment region, which by definition does not include fish around the Bismarck and Solomon Sea areas (figure 1).

For the 2015 (El Niño) experiment, simulated tag releases for the PNG and SOL locations showed similar patterns of dispersion (figure 4). Tagged fish from both release locations showed a greater movement north and east into oceanic waters than during the 2012 reference scenario. In particular, the movement of tagged individuals south from the Solomon Sea area was greatly reduced during the 2015 scenario. Simulated fish from the FSM location moved almost entirely east along the equatorial region.

For the untagged fish during the same year, the PNG and SOL locations again showed a dispersion similar to that of the tagged fish, for regions up to 5-degrees around the release. Above this, although there was an increased movement east of untagged fish compared to the reference scenario, fish were predominantly distributed south of the Solomon Sea area. For untagged fish around the FSM location, dispersion was weighted more heavily along the equator than in the reference scenario, except for the 20-degree scenario that included more fish in the Bismarck Sea that dispersed along the coast of Papua New Guinea and Indonesia.

For the 2010 (La Niña) experiment, simulated tag releases again showed differing results (figure 5). The PNG release showed dispersion similar to the 2012 reference scenario, but with easterly movement by only very few fish and a greater number of fishing moving west well into the Indonesian archipelago. By contrast, the SOL release showed most tagged fish moving south-east into the Solomon Islands archipelago, with very few moving south towards the coral sea or west along the coast of Papua New Guinea. For the oceanic FSM released fish, movement contrasted that of the El Niño scenario with a near exclusive movement west towards Indonesia and Palau.

For untagged fish around the PNG location during the same period, there was a very similar dispersion to tagged fish even for groups up to 10 degrees around the release location, although a portion of this latter group also exhibited movement into the Solomon Islands archipelago similar to the tagged SOL individuals. Once the size of the untagged group increased to a 20 degree diameter around the tagging location however, this was sufficient to include many fish residing south of Papua New Guinea and those moving into the Coral Sea. As the area including untagged fish increased around the SOL tagging location, the proportion of fish moving in a similar fashion to those of the PNG release increased. By the 5-degree area scenarios around the release location, large proportions of untagged fish moved west towards Indonesia in place of moving southeast into the Solomon Islands. At 10-degree and greater scenarios, the dispersion of untagged fish was very different to those of the tagged fish. Finally, for the untagged individuals around the FSM release location, fish showed a very similar dispersion to tagged fish up until the 10-degree scenario, at which point untagged fish included fish close to both the PNG and SOL release scenarios, and exhibited a similar dispersion dominated by the westward movement to Indonesia and southeast movement into the Solomon Islands, respectively. However, at the scale of the true assessment region, untagged fish had a less dissimilar dispersion to the tagged fish, albeit with increased presence and movements south towards Vanuatu and the Coral Sea.

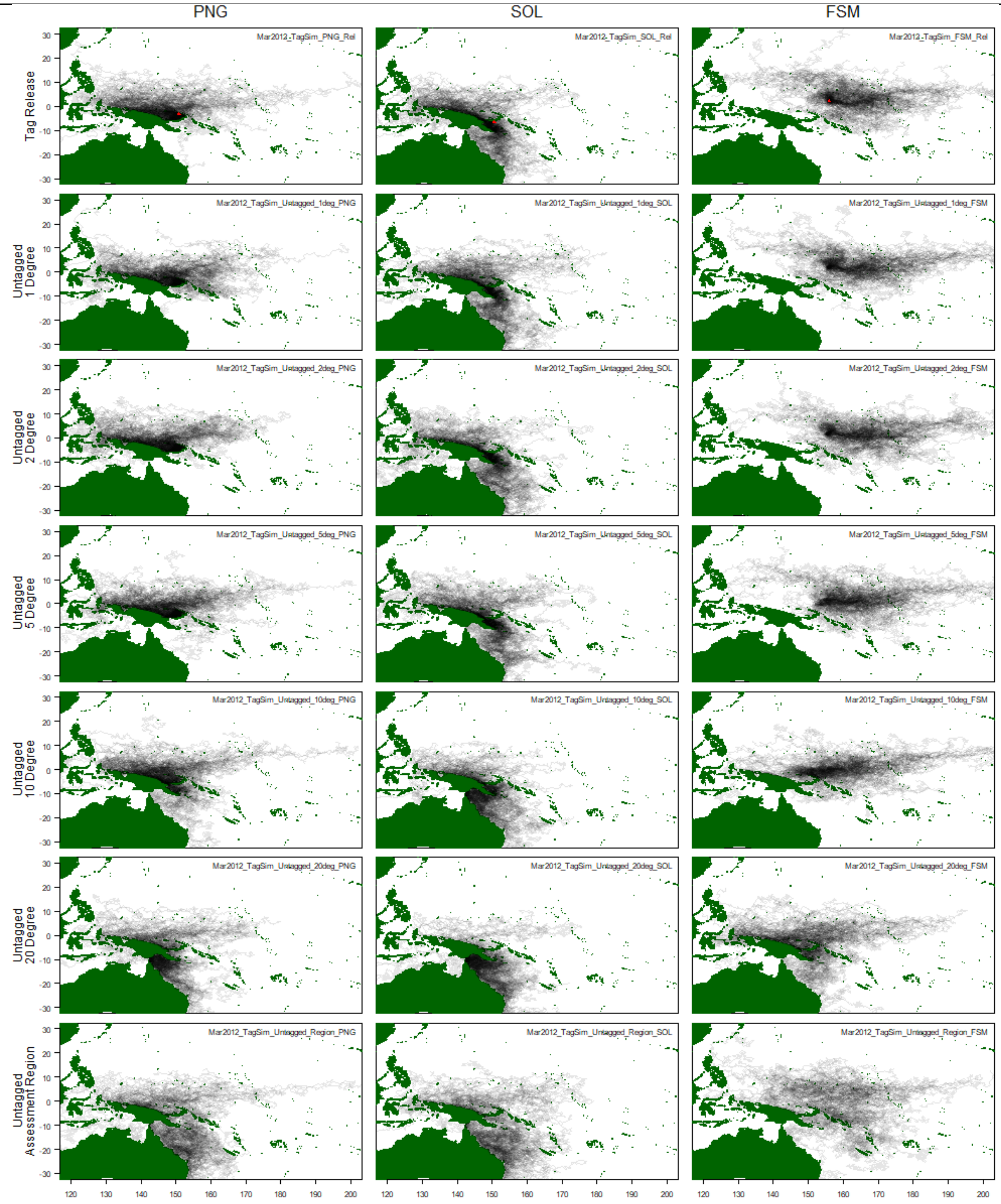

Figure A1. Dispersion after 270 days of 100 example trajectories of all scenarios during the 2012 ENSO-neutral reference scenario.

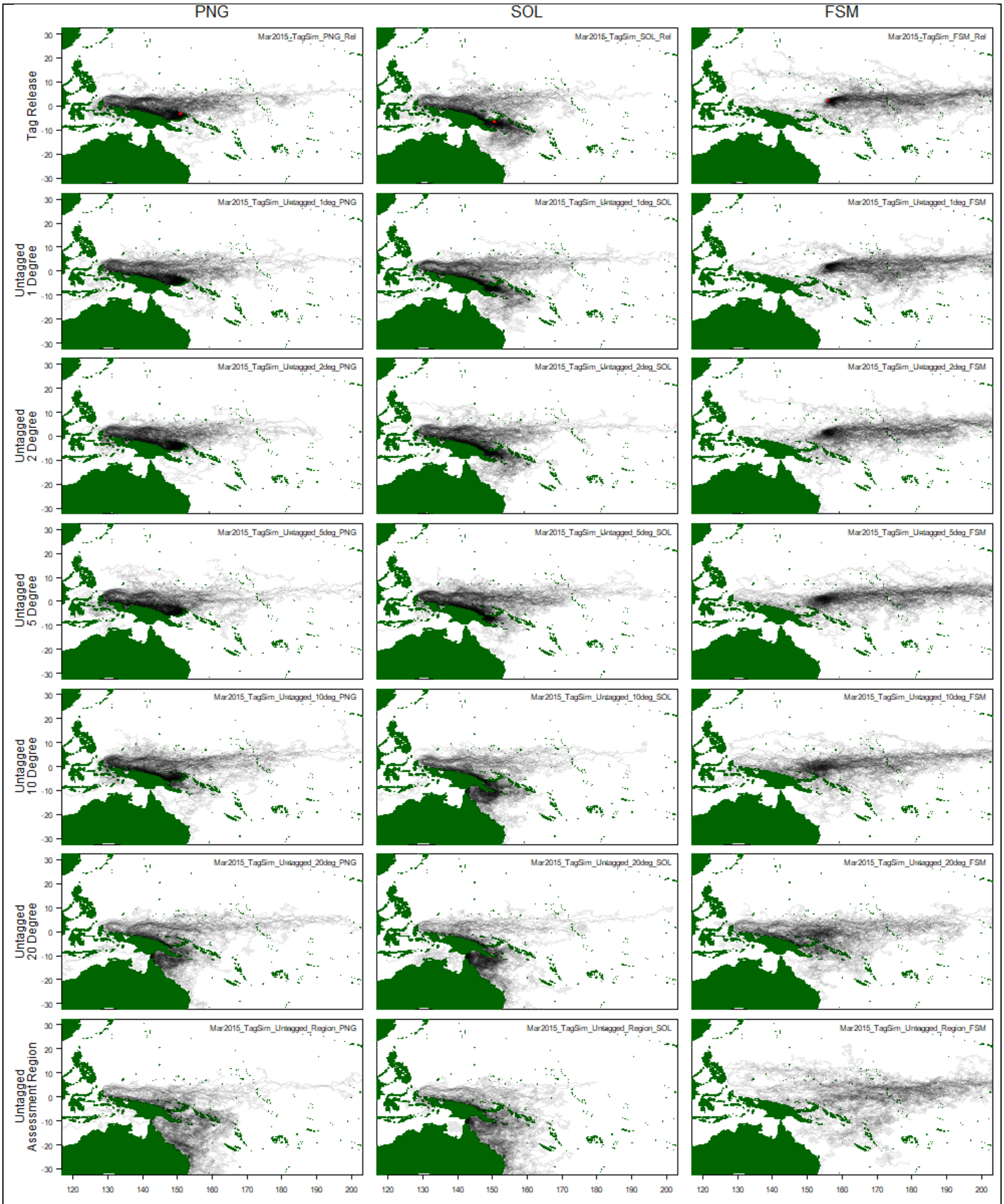

Figure A2. Dispersion after 270 days of 100 example trajectories of all scenarios during the 2015 El Niño reference scenario.

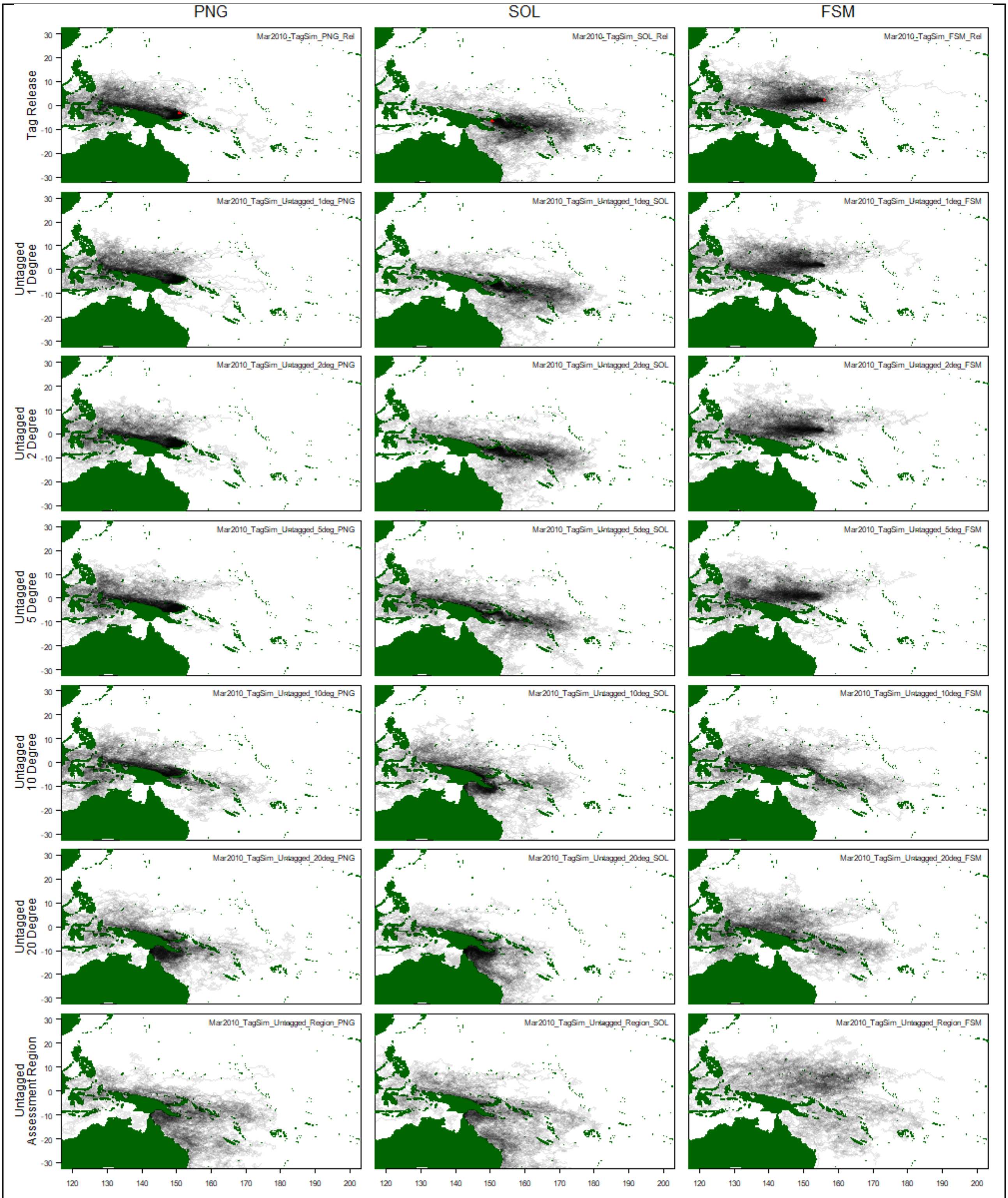

Figure A3. Dispersion after 270 days of 100 example trajectories of all scenarios during the 2010 La Niña reference scenario.

5.2 Fishing Pressure

To demonstrate the variability in fishing pressure experienced by tagged and untagged groups of simulated fish across our scenarios, the distribution of probability of capture by time t (equation 3) was plotted for all fish in each group at monthly increments (figures 6-8).

For the ENSO-neutral 2012 reference scenario, the probability of capture varied across all tagged fish groups, as well as between tagged fish and their corresponding untagged counterparts (figure 6). The median probability of recapture increased rapidly for both PNG and SOL tagged fish during the first 90 days at liberty. This increase began to asymptote for SOL tagged fish, but continued for the PNG release until 150 days at liberty, before levelling off. In contrast, the FSM tagging release experienced much lower fishing pressure until 150 days at liberty, at which point a larger number of tagged individuals had moved into areas of high fishing pressure and the distribution widened. By the end of the 270 day simulation, PNG tagged individuals had a median probability of capture of 0.14 (interquartile range, IQR = 0.09), with a slight positive skew. This value was 0.07 (IQR = 0.12) for SOL tagged fish, with a near normal distribution, and was 0.06 (IQR = 0.09) for FSM tagged fish with positive skewed distribution.

For untagged fish groups over increasing areas around the release location, these distributions were very similar up to 5-degrees around the tagging location for the PNG and SOL releases, even after 60 days. For FSM scenarios, this was only the case up to 2-degrees. In these cases, the distribution of experienced fishing pressure for untagged fish over larger areas rapidly departed from the tagged fish group from the beginning of the scenario. This was not the case, however, for untagged fish in the actual assessment region of the FSM release, which experienced a fishing pressure very similar to the tagged release group from 30 days onwards, albeit with a lower median and greater variation in probability of capture. In the case of the PNG and SOL scenarios large areas and the assessment regions of untagged fish were consistently and significantly under-depleted compared to their corresponding tag release groups.

For the 2015 (El Niño) experiment, patterns in fishing pressure across and between groups were similar to those of the reference scenario, although probability of recapture was lower for most tagged and untagged fish at the PNG and FSM locations, but higher for those release at and around the SOL location (figure 7). The rate of increase in median recapture probability was also similar to the reference scenario. Of note is that, even by 30 days the distribution of recapture probability between tagged and untagged fish up to 10-degrees around the PNG location was very similar and remained so until the end of the 270 day simulation. In the case of both the PNG and SOL groups, untagged fish at the assessment region scale were again much more under-depleted than the tagged fish, though less so compared to the reference scenario.

FSM groups also varied similarly to the reference scenario, in that they were increasingly over-depleted compared to the tag release group up until the level of the stock assessment level, which was under-fished but with a similar distribution compared to the tagged fish. At the end of the 270-day simulation, the median recapture probabilities were 0.12 (IQR = 0.08), 0.09 (IQR = 0.08) and 0.03 (IQR = 0.07) for the PNG, SOL and FSM release groups, respectively.

For the 2010 (La Niña) experiment, fishing pressure was the lowest for PNG tagged fish, comparable for SOL fish, and much higher for the FSM release fish (figure 8). In general, the variability in experienced fishing pressure was lower for most groups during this scenario. In the case of the PNG and SOL untagged groups, probability of capture was again comparable to tagged fish up to a 5-

degree area around the release location. Beyond this scale, untagged fish were again underdepleted compared to the tagged fish, though less so than in the reference scenario.

The FSM groups showed very different patterns of fishing pressure. During the first 90 days, there was a similar pattern as in previous scenarios, with untagged fish at increasing scales around the release location overfished compared to the tagged group. By the end of the 270-day simulation however, all the FSM groups except the assessment region group had very similar distributions of recapture. The median probabilities of recapture were 0.10 (IQR = 0.05), 0.08 (IQR = 0.06) and 0.09 (IQR = 0.09), for the PNG, SOL and FSM scenarios, respectively, by the end of the simulation.

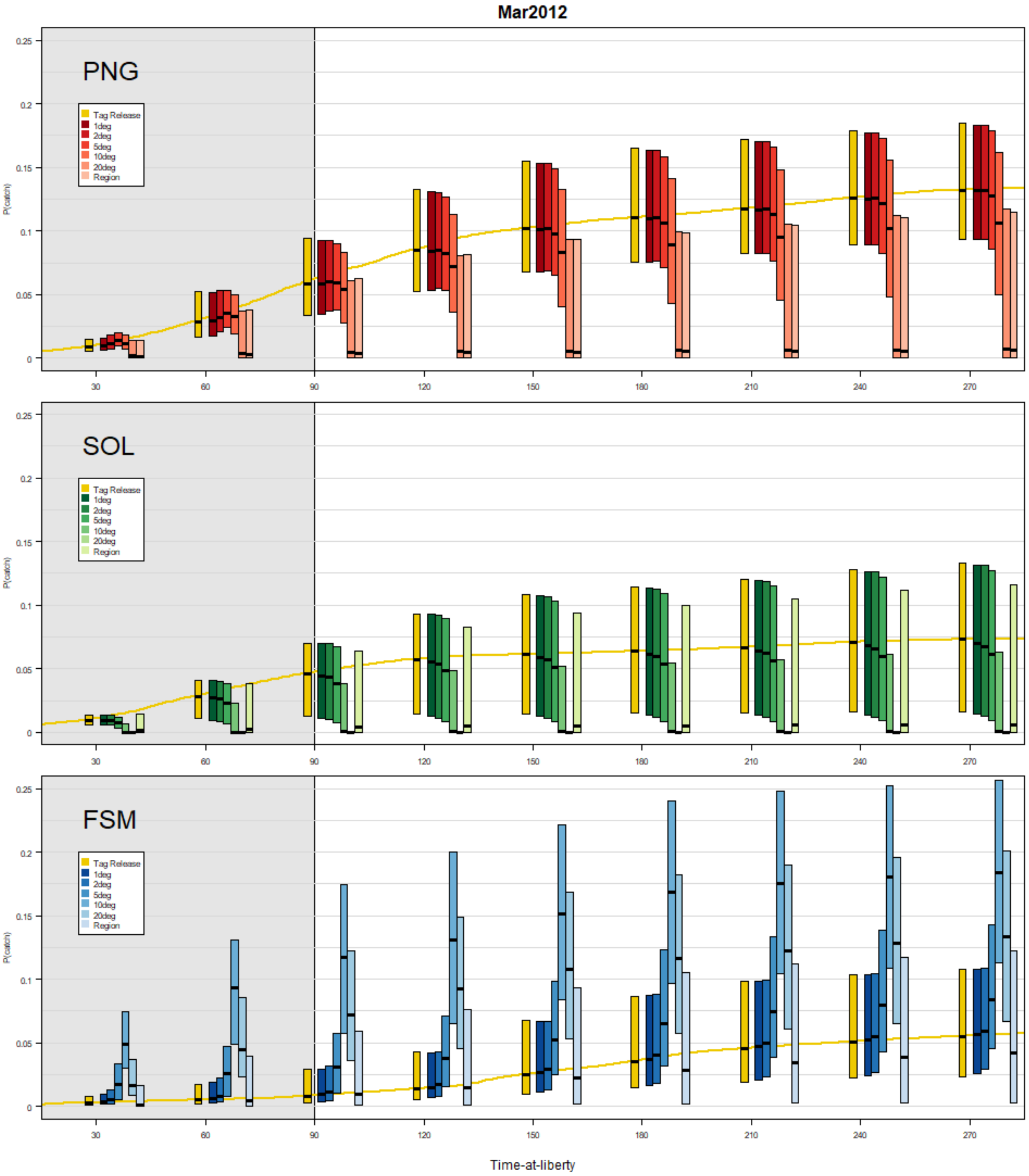

Figure A4. . Boxplots showing the median and interquartile ranges of recapture probability for tagged and all untagged fish groups through time for reference ENSO-neutral 2012 scenario. The daily median recapture probability of the tagged group is shown with a yellow line.

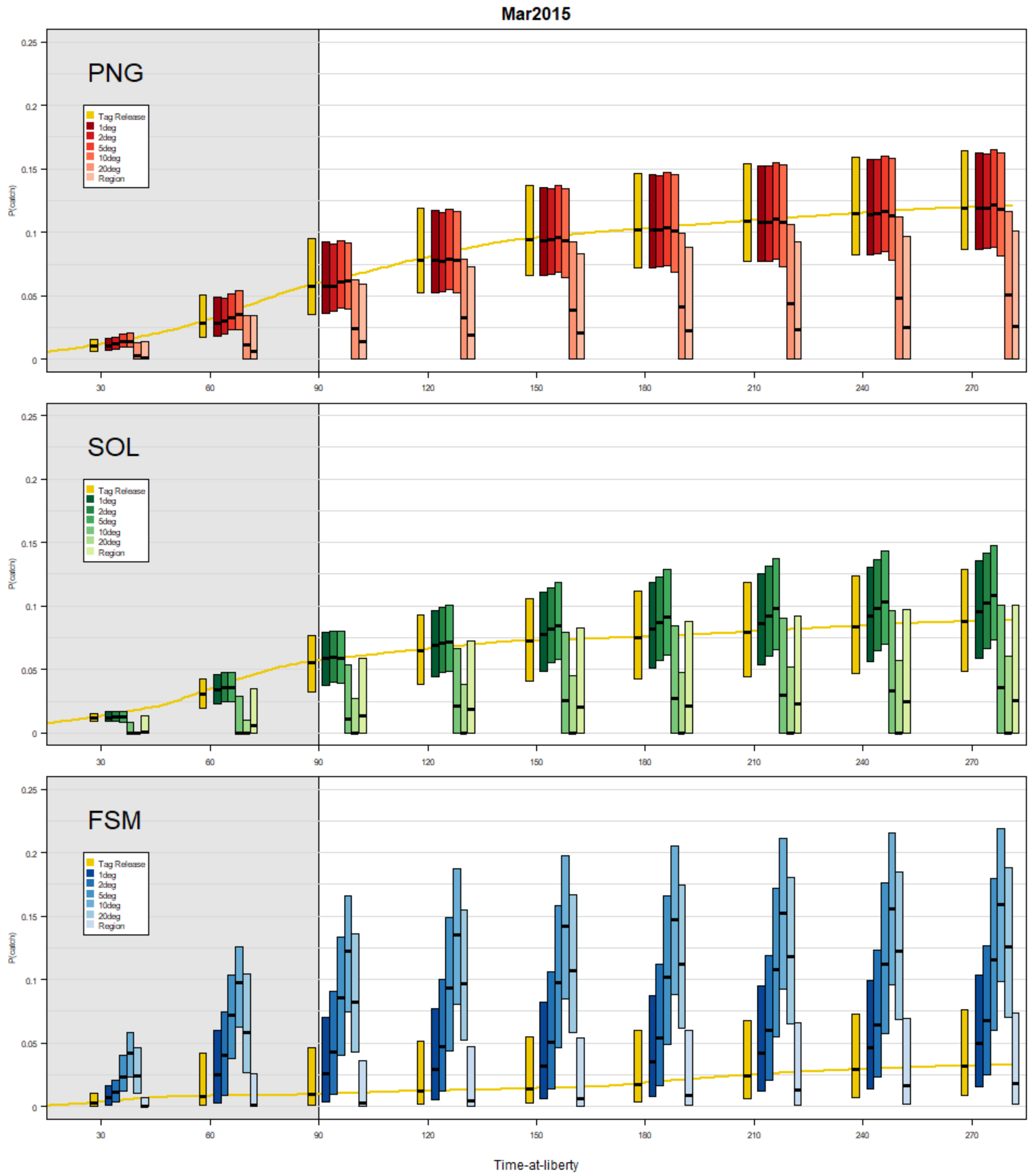

Figure A5. Boxplots showing the median and interquartile ranges of recapture probability for tagged and all untagged fish groups through time for 2015 El Niño scenario. The daily median recapture probability of the tagged group is shown

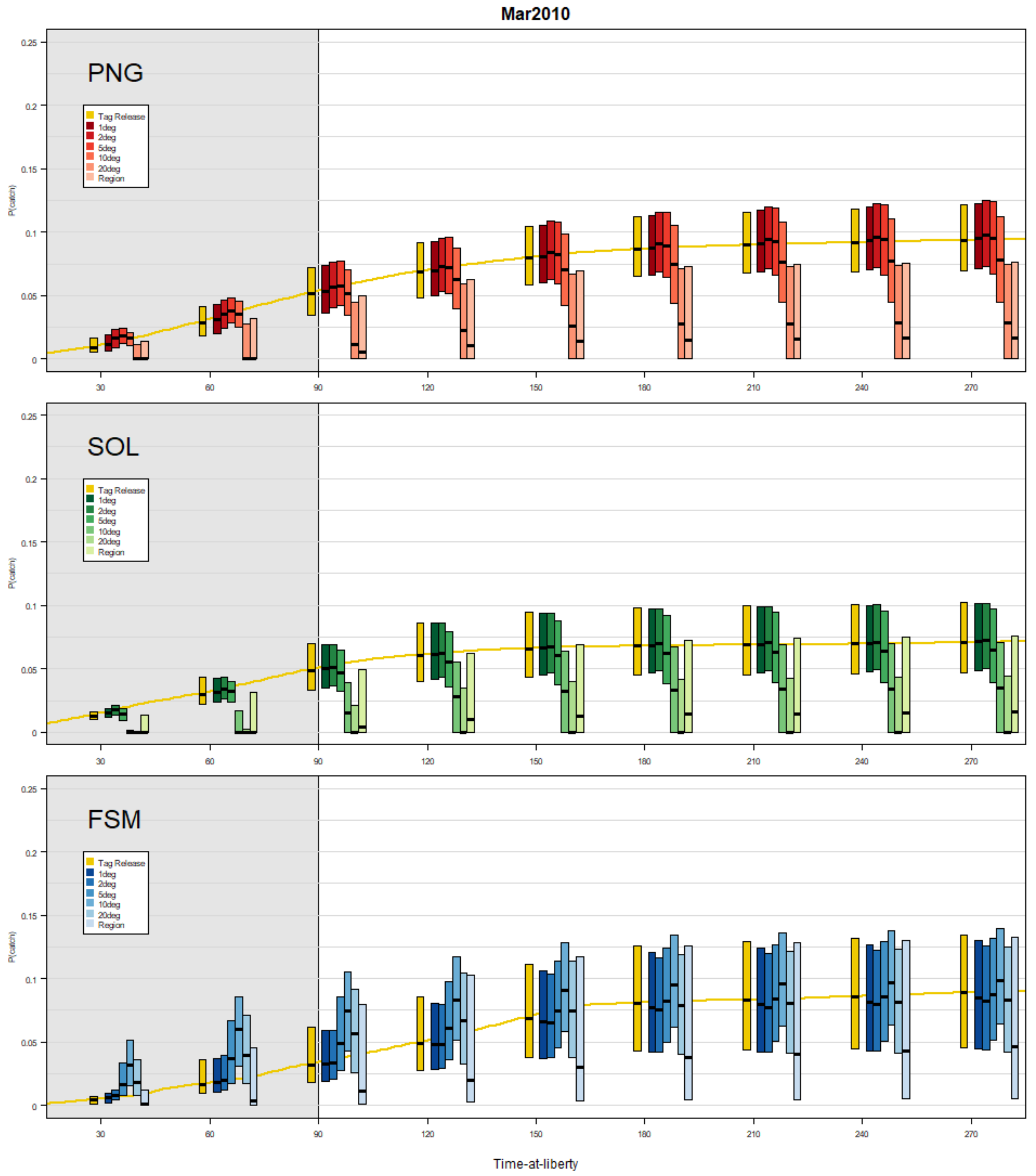

Figure A6. Boxplots showing the median and interquartile ranges of recapture probability for tagged and all untagged fish groups through time for 2010 La Niña scenario. The daily median recapture probability of the tagged group is shown