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A SUMMARY OF BLUEFIN TUNA ELECTRONIC AND CONVENTIONAL TAGGING DATA

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SUMMARY

As of June 2016, ICCAT has received summary data from 722 electronic tags deployed on Atlantic Bluefin tuna in the Gulf of Mexico, western Atlantic, Gulf of St. Lawrence, east and southeast Atlantic and west and east Mediterranean Sea. These deployments span 15 years beginning in 2001 and involved fish between 16 to 499 kg and 56 to 302 cm in size. An exploratory look at the data in its aggregated form is provided and its usefulness as a basis for developing Bluefin tuna movement models is considered. The observed patterns are evaluated against patterns emerging from a view of ICCAT's conventional Bluefin tuna tagging data.

RÉSUMÉ

Au mois de juin 2016, l'ICCAT avait reçu des données récapitulatives de 722 marques électroniques apposées sur des thons rouges de l'Atlantique dans le golfe du Mexique, l'Atlantique Ouest, le golfe du Saint-Laurent, l'Atlantique Est et Sud-Est et la mer Méditerranée occidentale et orientale. Ces appositions de marques ont été réalisées pendant 15 ans à compter de 2001 et concernaient des poissons pesant entre 16 et 499 kg et mesurant entre 56 et 302 cm. Un examen exploratoire des données dans son formulaire agrégé est présenté et son utilité en tant que base pour développer des modèles de déplacement du thon rouge est examinée. Les schémas observés sont évalués par rapport aux schémas provenant de l'observation des données de marquage conventionnelles de thon rouge de l'ICCAT.

RESUMEN

A junio de 2016, ICCAT ha recibido datos resumidos de 722 marcas electrónicas colocadas en atunes rojos del Atlántico en el golfo de México, en el Atlántico occidental, en el golfo de San Lorenzo, en el Atlántico este y sudeste y en el mar Mediterráneo occidental y oriental. Estas operaciones de marcado se han realizado durante 15 años, desde 2001, en ejemplares con un peso de entre 16 y 499 kg y una talla de entre 56 y 302 cm. Se considera la realización de una observación exploratoria de los datos en su forma agregada y de su utilidad como base para desarrollar modelos de movimiento de atún rojo. Se evalúan los patrones observados con respecto a los patrones procedentes de la observación de los datos ICCAT de marcado convencional de atún rojo.

KEYWORDS

Electronic tags, Bluefin tuna, Movement

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1. Introduction

Bluefin tuna tracking studies have a long history beginning in the 1940's using conventional tags and for the past 20 years using pop-up satellite and archival tags (etags). ICCAT currently maintains and administers a conventional tag database that details the deployment and recovery information and metadata for Bluefin tuna and 11 other large pelagic fish species. It also has an inventory of electronic tag deployments but this does not include detailed movement information. The absence of the detailed movement data has limited the development of both well-informed Bluefin tuna movement models and assessment models that are sensitive to the trans-Atlantic migrations of the eastern and western populations.

In order to take full advantage of the etag information that currently exists, the SCRS, on behalf of the Bluefin tuna Working Group, recently requested that Bluefin tuna researchers contribute their etag data in an aggregated format that would limit its usefulness to only describing the coarse movement dynamics of the species. In little over a year, 14 laboratories and institutions have donated their data on 722 tagged fish (**Table 1**).

Our goal here is to describe the data that was contributed and evaluate its potential for providing the necessary movement information. The observed patterns will be compared with existing notions of Bluefin tuna movement and with patterns inferred from the conventional tagging data.

2. Methods

The two sources of tagging data contributed to the description of Bluefin tuna movements. The conventional tag database maintained by ICCAT provided high resolution location information for a fish at the moment of first capture and at recapture. The intervening time could be many years or several days. The second source was aggregated etag data which provided low resolution position information (i.e. area) where the duration of the deployment was maximally one year for pop-up tags and several years for archival tags.

To facilitate comparisons between the two data sources, the high resolution conventional data was mapped to the same areas as the etag data. These areas are shown in **Figure 1**.

2.1 ICCAT Conventional tagging database

The database (see: http://iccat.int/en/accesingdb.htm) compiles mark and recapture events from 1940 until 2014 on 5,345 fish from both sides of the Atlantic, although 87% of fish were tagged in the western Atlantic (including GOM and CAR, **Table 2**). The remainder was tagged mainly in the western Mediterranean and East and Southeast Atlantic (**Table 2**). There were 1275 tagging events of which 93% tagged 10 tuna or less and 0.5% tagged 100-240 tuna.

The database contains the length and or weight at tagging and recapture albeit with measurement errors, imprecisions due to some lengths and weights being estimated instead of measured, and missing values. The measurement error is most influential/obvious for fish that have been recaptured after a short time at large. The position at release and recapture were provided with latitude and longitude for each fish.

2.2 The new ICCAT etag database

The aggregated Bluefin tuna etag data (2001-2015) contributed by 14 investigators was pooled in a common database. Associated with each deployment was a PTT number, estimate of fish size, contributing institution, contact person and the summarized geolocation data. Given frequent collaborations between researchers and the recycling of "unique" PTT numbers, it was necessary to check the data for duplicates.

Detailed tag tracks should provide 2 geolocations for each day at large; however gaps in the track can occur. The aggregated geolocation data indicated only the date of entry into one of 11 predefined broad geographical areas and the corresponding days at large within each area. These larger areas were the Gulf of St. Lawrence (GSL), Western Atlantic (W_ATL), Gulf of Mexico (GOM), Caribbean (CAR), North Central Atlantic (NC_ATL), South Central Atlantic (SC_ATL), Northeast Atlantic (NE_ATL), Southeast Atlantic (SE_ATL), East Atlantic (E_ATL) and Western and Eastern Mediterranean (W_MED and E_MED) (**Figure 1**). Due to data gaps in the detailed geolocation data, it was necessary to verify that the days at large within each area equaled the total days at large. Finally, the data was disaggregated temporally by creating a separate record for each month that a fish was resident in an area. This facilitated an exploration of movements on a monthly time step.

2.3 Maturity stages/size categories

Given that movement of juvenile Bluefin tuna could be quite different from that of mature adults, each fish in both the conventional and etag databases was assigned to one of 3 maturity stages/size categories using the contributed fish size information. This required an estimate of the age of each fish using its size information and an appropriate growth equation. In the interest of having the size categories align with maturity stages, it was necessary to resolve the issue of there being different maturity schedules for the western and eastern Bluefin tuna populations and different growth equations.

The ICCAT manual (ICCAT 2006-2016) provides separate growth equations for the eastern and western populations but to use them one must know the origin of the tagged fish. Origin cannot be safely inferred from tagging site given the trans-Atlantic migration of even young Bluefin tuna. However, given that the most recent growth equation developed in Restrepo *et al.* (2009) for the western population is very similar to that proposed for the eastern population in the ICCAT manual (**Figure 2**), the age-length and age-weight relationship from Restrepo *et al.* (2009) was used for both East and West populations.

The age at maturity for the eastern and western populations is assumed to be 4 and 9, respectively (Richardson et al. 2016). Using Restrepo *et al.* (2009), this equates with mature fish having a fork length larger than 115 cm or a weight heavier than 31 kg in the east and thresholds of 187 cm and 129 kg in the west. These thresholds create 3 maturity stages as follows:

1. Juvenile1: length < 115 cm or weight < 31 kg (age ~4)

2. Mature: length > 187 cm and weight > 129 kg (age ~8)

3. Juvenile2: length and weight > Juvenile1 but less than Mature

Under current assumptions about the 2 populations, the middle maturity class (Juvenile2) contains both mature eastern fish and immature western fish. Thus one can flexibly combine the Juvenile2 with the Matures if one believes that age at maturity was overestimated in the western Atlantic population as suggested in Richardson (2016).

An absence of size data prevented maturity stage assignment for 36 etagged and 348 conventional tagged fish. The 36 etagged fish lacking size data were all associated with eastern tagging sites.

Maturity stages were assigned to measurements at both release and recapture and transcription errors were identified and corrected according to the following rules:

1. Fish that were released as Mature have to be Mature at recapture.

2. Fish that were Juvenile2 at recapture have to be at least Juvenile2 at recapture unless body weight is greater than 129 kg.

3. Fish recaptured as Juvenile1 9 years or more after release are assumed to be Mature.

Functions for estimating length (cm) given weight (kg) were:

1. Length for western Bluefin tuna = 382 * (1-exp(-0.0798*(Weight+0.707)))) ; (Turner and Restrepo 1994 in the ICCAT manual)

2. Length for western Bluefin tuna = 314.9 * (1-exp(-0.089*(Weight+1.13)))) ; (Restrepo *et al.* 2009)

3. Length for eastern Bluefin tuna = 318.85 * (1-exp(-0.093*(Weight+0.97)))) ; (Cort 1991 in the ICCAT manual)

2.4 Sojourn times and transition intensities

For each etagged Bluefin tuna, the consecutive pairs of locations visited in chronological order were compiled in a sequence or frequency matrix where rows were the starting location and columns were the arrival location. Observed transition frequencies, on a monthly time step, were calculated both for all etagged fish and for each size category. The transition frequencies were estimated using the msm ackage developed under R by Jackson 2011. Diagrams were produced with igraph (Csardi and Nepusz 2006; Csardi 2015).

A multi-state continuous time Markov model was fit to the transition frequency matrix that included all the tag data (Jackson 2011) using maximum likelihood. This model estimates both the sojourn/holding times of fish in each area, the probability of transitioning to an adjoining area and transition intensities. Jackson (2011) indicates that a more practically meaningful parameterization of a continuous-time Markov model with transition intensities q_{rs} is in terms of the mean sojourn times $-1/q_{rr}$ in each state *r* and the probabilities that the next move of the process when in state *r* is to state *s* (i.e., $-q_{rs}/q_{rr}$). A graphic representation of the intensity/rate matrix Q defining the allowable transitions is given in **Figure 17**. The transition matrix P which provides the probability of occupying the new state *s* conditional on occupying state *r* for time *t* is related to the intensity/rate matrix Q as follows: $P(t) = e^{(tQ)}$.

The frequency of the observed states were modelled as a function of the observation time (Julian start day plus elapsed days) with the transition intensities between states dependent on a season covariate. Transition intensities/rates govern both the time spent in the current state and the probabilities of the next state. The data was assumed to be the product of an observation of the process at an arbitrary time (a "snapshot" of the process) with the states unknown between observation times. The seasons were defined as follows: NDJF, MAMJ and JASO.

Models were also developed using covariates with smaller time blocks or including a fish maturity/size covariate. These did not converge. Also because of convergence issues, the 11 initial areas were aggregated to form 8 by combining the Northeast and East Atlantic (Northeast Atlantic), the East and West Mediterranean Sea (Mediterranean) and the North and South Central Atlantic (Central Atlantic).

The approach for the conventionally tagged Bluefin tuna was similar though it must be recognized that the interval for transitions was not fixed. Nevertheless, a simple Markov chain approach was applied using the markovchain package (Spedicato *et al.* 2016) and transition probabilities estimated.

2.5 Track estimation

The contributed etag data underwent some form of track estimation prior to being aggregated and submitted to ICCAT. Each investigator took a slightly different approach to estimating the geolocations and because their protocols are not standardized, the transition probabilities will be affected. The most obvious effect is on the sequence of state transitions. The states may be wrongly estimated and the transitions may be erratic (shift between two areas multiple times). A description of the estimation process is provided for the Canadian tags in an effort to establish a standard protocol.

The most probable tracks were estimated based on data stored in satellite tags (light, sea surface temperature and depth), using the package Trackit (Lam *et al.* 2010) for most tags, and with Ukfsst (Lam *et al.* 2008) when necessary. Both packages are running in the environment R ((R Core Team 2013). Briefly, Trackit estimates the position based on the level of light at sunset and sunrise and surface temperature as measured by the tag while trying to minimize the difference in conditions between the predicted and measured position. It uses an unscented Kalman filter to handle non-linearity in the model. To avoid being caught in a local minimum and remove the operator’s influence in the process, several trials were performed starting with various initial parameter values and/or keeping some parameters at default values to simplify the model. The retained solution had the lowest negative log-likelihood value although typically a large proportion of the trials yielded similar solutions. The Ukfsst package estimates tracks based on sea surface temperature and raw geolocations obtained from proprietary Wildlife computer software (DAP) using light measurements, and using a Kalman filter. Both these packages use the same random walk model and include diffusion and drifting. None of these models are able to avoid land in estimating best locations.

In a second step, the estimated tracks were corrected using the daily maximum depth recorded by the tag compared with the depth at the estimated position and adjusted appropriately when necessary. Briefly, when the measured maximum depth was deeper than the depth at the estimated position, 300 locations were sampled within the confidence interval ellipse and the new position was calculated as the nearest location with a suitable depth. A slightly modified version of the add-on package MakeBtrack.R was used for this purpose.

3. Results

3.1 ICCAT electronic tagging in the West Atlantic

The range of Bluefin tuna was divided into 11 large geographic areas (**Figure 1**) which relate to known spawning areas (e.g. Gulf of Mexico and Mediterranean Sea), juvenile foraging grounds (e.g. Western and Eastern Atlantic) and adult foraging grounds (e.g. Gulf of St. Lawrence and North East Atlantic). Etags were deployed in 7 of these areas, not including the Caribbean, North East Atlantic and Central North and South Atlantic (**Figure 3**).

In the West, the prime tagging site was the Western Atlantic (316) followed by the Gulf of St. Lawrence (100) and Gulf of Mexico (31) (**Table 4**). The top 2 tagging months in the Western Atlantic were August and September whereas April and May was the focus in the Gulf of Mexico. The most deployments in the East were in the Western Mediterranean Sea (120) followed by the South East Atlantic (81) and lastly the Eastern Atlantic and Eastern Mediterranean Sea (37 each). Top deployment month varied by region with June/July being the focus in the Western Mediterranean Sea compared with May/November in the Eastern Mediterranean. The majority of tags were deployed in May and October in the South East Atlantic and August/September in the East Atlantic **Table 4**).

In the West, the Juvenile1 class was only tagged in the Western Atlantic but in three locations in the East (Eastern and South Eastern Atlantic and Western Mediterranean Sea) (**Figure 3**). Mature fish were tagged in all 7 tagging areas except the Eastern Atlantic and Juvenile2 fish were similar but were also not tagged in the Gulf of Mexico. The average length of fish tagged in western areas was consistent across months within each area (**Figure 4**). The average length in the Gulf of St Lawrence was 250 cm compared with 225 cm in the Gulf of Mexico and at most 200 cm in the Western Atlantic. In the East, fish length declined from a high of 250 cm in May to a low of 100 cm in October.

Tuna released with conventional tags were mainly juveniles (86%) and a small proportion was at sea long enough to become mature at recapture (**Table 5**).

Days at large differed between Western and Eastern deployments (**Figure 5**). For fish over 150 cm deployments were at most an average of 5 months in the West and at most 2.5 months in the east. In the Gulf of Mexico the days at large were no better than an average of 2.5 months and in the Mediterranean no better than 1 or 2 months. Similarly, fish less than 150 cm had longer deployments in the West (8 months) compared to the East (4 to 5 months). The relationship between deployment time, management zone and length of deployment is clearly shown in **Figure 6** for all 722 fish. Very few tags remain on a fish for a full year which for the Eastern deployments, where deployments start in May, means that there is little location data available for fish between 1 January and 30 April.

In general, the shorter the time at large, the higher probability a tuna would be close to its tagging site. A dwindling number of tags left by March and April limits interpretation and information on the possible migration routes. Sojourn times indicated that fish tagged in the West did not spend time in the North East Atlantic or the Eastern Mediterranean and that fish tagged in the East did not spend any time in the Caribbean, Gulf of Mexico or Gulf of St. Lawrence (**Figure 7**). The longest sojourn times were in the Western and Eastern Atlantic and Western Mediterranean Sea (~ 125 days). The proportion of the total days at large was over 75% for both the Eastern and Western Mediterranean Sea and the Western Atlantic. Because the deployments are left truncated, we do not know when a fish started its sojourn in the area it was tagged in and in those situations expect a shorter sojourn.

Figure 8 provides an indication of the percentage of the total deployment spent in each area for fish tagged in each of the 7 areas. It shows the areas visited from each starting point and the percentage of the total deployment spent there. The sojourn in the tagging area tended to be a big proportion of the total time at large possibly due to generally short tag retention times. Consider for example the proportion of time spent in the Gulf of St. Lawrence by fish tagged there versus the Western Atlantic or Gulf of Mexico.

Sojourn times can also be considered in relation to the maturity class of the fish carrying tags (**Figure 9**). All western tagged fish in the Juvenile1 class remained in the Western Atlantic despite deployment times longer than the eastern tagged Juvenile1 fish which made trans-Atlantic migrations to the Western Atlantic and runs into the Western Mediterranean Sea. Conversely, Juvenile2 fish tagged in the West showed activity in the Central and Eastern Atlantic and Gulf of St, Lawrence while similar sized fish tagged in the East remained in the Mediterranean Sea or ventured into the Southeast Atlantic. Mature sized fish from both deployment zones were active across a large number of areas despite somewhat shorter deployments recorded for the Eastern fish. West tagged fish did not reach the Eastern Mediterranean Sea or Northeast Atlantic while the East tagged fish did not enter the Caribbean, Gulf of St. Lawrence or Gulf of Mexico. The sojourn duration relative to the total deployment and number of sojourns in an area differed by fish size class and area. A large proportion of time spent in an area may be a feature of a particular size class but short tag deployments or the seasonal timing of deployments can also produce this type of bias. Also, frequent sojourns to an area may be a function of tagging area and short deployment but it could also reflect its position along a route.

The effect of tag deployment duration was demonstrated by limiting the data plotted to only deployments longer than 30 days (**Figure 10**) and comparing it with days at liberty from 30 to 120 days in length (**Figure 11**; top panel) and 120 to 230 days long (**Figure 11**; bottom panel). When days at large were below 120, the Juvenile1 sized fish did not appear in areas outside the tag deployment area. By day 230 the Juvenile1 fish tagged in the East entered neighboring areas. The Juvnile1 fish tagged in the West stayed within the same area even after 334 days. In contrast, the Juvenile2 fish tagged in the East did not occur outside the area in which they were tagged, even after 120, 230 and 334 days. Those tagged in the West appeared in eastern areas around day 230. Lastly Mature sized fish tagged in the West occurred in the East and Southeast Atlantic by 120 days while East tagged fish occurred only in the East and Northeast Atlantic. By 230 days the West tagged fish occurred in all eastern areas except the Northeast and Eastern Mediterranean Sea and the East tagged fish reached the Western Atlantic. Generally speaking, deployments longer than 240 days show outward migrations of Mature sized fish quite well but had limited large scale movement for the Juvenile size classes. This interpretation is biased by the season and/or area of deployment.

3.2 ICCAT Conventional tagging

Conventional tagging showed that 3% of the fish tagged in West Atlantic were recaptured in the East, Southeast and Northeast Atlantic while 1% was recaptured in the Mediterranean Sea (**Table 6**). Conversely 5% of fish tagged in the East Atlantic were recovered in the West Atlantic.

Time spent at sea after tagging varied from 1 day to 40 years with 1932 fish at large for less than 90 days, 3371 (63%) fish at large for up to a year, and 96% recaptured within 5 years (**Figure 12**). The long deployment durations resulted in fish growing into the larger size classes by the time of their recapture. Three to four year old fish in the Juvenile1 size class are expected to become Mature sized fish by age 8 to 9. In fact, 4 fish released in the West Atlantic grew from Juvenile1 to Mature within 3 years (we ignore the occurrence of Juvenile1 fish recaptured as Mature sized fish after only 1 year) (**Figure 13**). Two were recaptured in the Southeast Atlantic and West Mediterranean Sea and the other 2 were recaught in the West Atlantic. Only 8% of fish at large for 6 to 9 years, after tagging in the West as Juvenile1, were recaptured in eastern regions as Mature sized fish. In contrast, 1 of 4 fish tagged in the East was recovered in the West Atlantic after 7 years (**Figure 13**).

142 Juvenile2 sized fish were tagged in the West Atlantic and grew to Mature size by recapture. Of these, 30 (21%) were recaptured in the East after mainly 4-6 years but also as early as 2-3 years (**Figure 14**). None of the 9 Juvenile2 sized fish tagged in the East were recaptured in the West (more detailed movement maps for the first year are given in **Appendix 1**).

3167 Juvenile sized fish were recaptured as Juveniles with 2082 (66%) recaptured within the first year. 2699 (85%) were tagged in the West Atlantic and 3.6% were recaptured in the East. Of the 411 fish tagged in the East, 18 (4.3%) crossed to the West within 6 years at large (**Figure 15**). Generally, most Juvenile sized fish were recaptured in the same region they were released in.

In the West, 282 Mature sized fish were tagged and 19 (6.7%) were recaptured in the Gulf of Mexico in Feb-May (+1 tuna in Aug) while 10% were recaptured in the East (**Figure 16**). All Mature sized tuna tagged in the East side were recovered there except for 1 that travelled to the GSL within 1 year.

3.3 Sojourn times and transition probabilities

A continuous-time Markov model is fully specified by the mean sojourn times and the probability that each state is next (Jackson 2011). These estimates are provided in **Table 7** for each level of the season covariate. The probability that an adjacent area is next is always 1 when there is only one adjacent area. The areas along a route were more informative. The Central Atlantic, for example, indicated seasonal variation in the probability of fish moving into the West Atlantic as did the West Atlantic for fish moving in to the Central Atlantic. The relative magnitude of the probabilities of moving in one direction versus another, it must be remembered, may be biased by the size class of fish contributing to the movement and other factors.

The transition matrices and their directed digraphs appeared to be good summaries of the etag and conventional tag movements described with maps.

Figure 18 depicts the transitions frequencies for all etagged Bluefin tuna as well as each size category. The frequencies shown on each edge are a function of the proximity of an area to the tagging site, the duration of the tag deployment, the size of the area and the nature of the fish tagged. The digraph for the Juvenile1 size class shows that fish were mainly resident in the areas they were tagged. There is no eastern movement but there is some western movement. The digraph for the Juvenile2 size class shows the opposite tendency with evidence of a west to east movement but not the converse. In fact there is no edge linking the movement of West tagged fish to that of East tagged fish.

The digraph describing the movement of Mature sized fish included all possible nodes/states. The dominant routes were from the West Atlantic to either the Gulf of St. Lawrence or the Caribbean and from the Mediterranean to the Southeast Atlantic. These routes extended to the Gulf of Mexico in the West and Northeast Atlantic in the East with lower frequency while movement to the Central Atlantic was less common.

The probability of transitioning between states was estimated for each level of the season covariate (**Figure 19**). Initially the months were binned to reflect a winter movement period, a spring spawning period and a summer/fall foraging period, however such a generalization of the behavioral state of the fish did not seem appropriate for both the East and West or for a mixed composition of Juvenile and Mature fish. Acknowledging these differences in a more heavily parameterized model was not possible so no attempt will be made to interpret the seasonal groupings in terms of behavioral states. To some degree these digraphs reproduce the anticipated movements to and from areas expected in the different seasons. For example, the Mediterranean shows no substantial influx of fish in the winter months but does show increased probability of transition in the spring months coming from the Southeast Atlantic. This seems consistent with movement for spawning purposes. One would expect something similar for the Gulf of Mexico but it is not that obvious. There is some influx into the area in both the winter and spring months but not in the summer/fall which could be interpreted in a number of different ways and should involve consideration of the tag deployment durations of fish that could have entered the area, the timing of tagging in the Gulf of Mexico and how the months were binned.

In a second example of the realism of the transitions, we can compare the influx of fish into the Gulf of St. Lawrence in each season and observe that no influx occurs except in the summer/fall season. This is consistent with what we expect and does not appear to be a function of sampling bias. This type of subjective appreciation of the movement should be completed for each area though it was not done here. Over longer time intervals the system approaches an equilibrium state which appears to identify some issues with the etag data (bottom right, **Figure 19**). Notably, there are no transitions to the Gulf of Mexico, Caribbean, Mediterranean, Central and Southeast Atlantic which may speak to the lack of long term deployments which results in tagged fish returning to their tagging locations after a full year (assuming an annual cycle). The probability that each area will be occupied after an interval of 365 days (passage probability) is provided for each area after setting covariates to a mean level (**Table 8**). These probabilities are low for transitions where we expect a high value and suggest problems with the data rather. For example, passage to the Gulf of Mexico from the Caribbean is low given their proximity and the time interval. The passage to the Mediterranean from the Southeast Atlantic is much higher and much more reasonable. Passage probabilities can also be estimated for each level of the covariate if a more detailed assessment is desired.

Using a discrete Markov chain model the conventional tag data was used to estimate transition probabilities. These transitions were compared to those developed from the etags in order to determine if the movements were similar. The emergent patterns confirmed the flow of tuna among areas within each region and the migration routes from west to east (**Figure 20**, red lines) and from east to west (stippled lines). These data have their own sampling biases as well as complications related to the nonstandard time step for transitions; consequently a more in depth comparison and interpretation must be done with caution.

Discussion

Numerous studies exist documenting the movement of etagged Bluefin tuna (e.g. Galuardi *et al.* 2010, Stokesbury *et al.* 2004, Teo *et al.* 2007, Wilson *et al.* 2015) and recognizing the collective power of these Bluefin tuna etag sources to provide a fairly comprehensive overview of the dynamics of Bluefin tuna migration, ICCAT requested that this data be provide to them in an aggregated format. At the time of writing, 722 tags were made available from both eastern and western sources. Currently data from another ~40 etags is available for integration into the main dataset and it is expected that another ~400 will be contributed over the next year. These figures do not include studies that are currently underway which could conservatively contribute data from another ~50 etags by late 2017. All told, ICCAT and the Bluefin tuna Working Group should have data from ~1200 etags within the next 18 months.

The current review of the etagging data is for a significant proportion of what will become available and thus should provide a useful basis for deciding how it might inform the 2017 stock assessment. The major outcomes and concerns resulting from an exploration of the data and multi-state continuous time Markov chain analysis are as follows:

1. The etag data is the product of non-standard track estimation protocols adopted by the different contributing researchers. The track estimation process can incorporate corrections for SST, corrections for bathymetry and the software is always evolving. The details of the fitting can impact the estimate of location and consequently our interpretation of Bluefin tuna movement.

2. Accompanying size information for 36 etagged fish was absent and needs to be recovered in order for that data to be involved in a size specific determination of Bluefin tuna movement.

3. Most tags report early. It is not clear from the data if this is a function of tagging method, tagger or even water temperatures. Longer retention on young fish which are often removed from the water for tag insertion suggests that method is a factor. Deployments were longer in the West and in northern latitudes creating a potential bias by management zone and region within zone.

4. The etag deployments were generally not long enough to visualize an annual cycle of movement. The staggered deployments of tags over the year helped to offset the effect of short deployments somewhat by allowing us to resolve some of the movement in portions of the year when no tagging occurred however in some cases we would be switching to an entirely different size class of fish to cover off the gaps. Secondly, tagging sites were active in different seasons so there is a strong possibility that gaps are being filled by fish whose origin differs from those tagged earlier in the season within the same zone.

5. Some deployment areas are over represented in the data. Strategic deployment of tags would help to fill gaps in the annual movement if issues with deployment duration remain a problem. Tagging in the Central Atlantic would help to resolve the trans-Atlantic movements which tend to require longer duration deployments from current tagging sites.

6. Tag deployments were on average shorter in the East, particularly on the larger (>150 cm) fish. Short deployments over emphasize transitions between areas close to the area of deployment and bias sojourn times. Deployments must be longer than about 230 days in order to begin seeing large scale movements of mature sized fish while the Juvenile sized fish require deployment durations longer than a year in some cases.

7. Analyses based on the etag data must account for fish size, time of deployment, location of deployment, and at least the two way interactions. Current methods did not support a very complicated model. Galuardi et al. 2014 found that it was not possible to make transition matrices by season because of the lack of long trajectories extending past February. With access to more etags this was possible here though there were only 3 seasons.

8. The conventional tag database has a role to play in validating the movement models based on the etag data. For example, areas occupied by a given size class of fish after a year at large and tagged in a given area and a given month should coincide with the areas predicted to be occupied by the model.

9. Some areas are large relative to others and this may bias the transition probabilities into them and sojourn times within them.

10. Etag data spans 15 years over which we assume that the migrations have been relatively consistent.

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Table 1. The total number of unique electronic tags contributed to ICCAT by investigator and zone of deployment (as of 13 June 2016). Tags with missing information are not included in this accounting.

Zone	Investigator	Electronic Tags	Contact
East	AZTI	20	I_Arregi
East	COMBIOMA	16	A_DiNatale
East	ESP_IEO	13	F_Abascal
East	FEDERCOOPESCA	5	A_DiNatale
East	ICCAT_GBYP	49	A_DiNatale
East	UCA	46	G_Aranda
East	UNIMAR	40	A_Mariani
East	WWF	86	G_Quilez_Badia
Subtotal		**275**	
West	DFO	48	A_Hanke
West	DFO-ACADIA	37	A_Hanke
West	DFO-STANFORD	15	A_Hanke
West	DFO-UNH	5	A_Hanke
West	LPRC	311	M_Lutcavage
West	USA_NOAA	31	C_Brown
Subtotal		**447**	
Grand total		**722**	

Table 2. Tagging site and number of fish tagged with conventional tags.

Tagging site	CAR	GOM	GSL	W_ATL	E_ATL	E_MED	SC_ATL	SE_ATL	W_MED	**Total**
N tags	18	3	5	4636	352	1	1	103	226	**5345**

Table 3. Maturity stage of fish in the etag and conventional databases.

	Maturity stage				
Source	***Juvenile1***	***Juvenile2***	***Mature***	***NA***	***Sum***
West etags	7	107	332	1	447
East etags	65	49	126	35	275
Conventional tags[1]	4327	378	292	348	5345

[1] maturity at release time.

Table 4. Bluefin tuna tag deployment location by stock area, management zone and month.

Zone	Stock_Area	Month	N	Sub total	Zone	Stock_Area	Month	N	Sub total
East	W_MED	5	5		**West**	W_ATL	1	6	
East	W_MED	6	48		**West**	W_ATL	2	4	
East	W_MED	7	31		**West**	W_ATL	5	1	
East	W_MED	8	15		**West**	W_ATL	6	2	
East	W_MED	9	16		**West**	W_ATL	7	29	
East	W_MED	10	4		**West**	W_ATL	8	115	
East	W_MED	11	1	**120**	**West**	W_ATL	9	87	
East	SE_ATL	5	51		**West**	W_ATL	10	69	
East	SE_ATL	6	9		**West**	W_ATL	11	3	**316**
East	SE_ATL	9	4		**West**	GSL	8	31	
East	SE_ATL	10	14		**West**	GSL	9	48	
East	SE_ATL	11	3	**81**	**West**	GSL	10	19	
East	E_ATL	7	7		**West**	GSL	11	2	**100**
East	E_ATL	8	20		**West**	GOM	3	5	
East	E_ATL	9	10	**37**	**West**	GOM	4	8	
East	E_MED	5	30		**West**	GOM	5	18	**31**
East	E_MED	11	7	**37**					

Table 5. Maturity stage at release and recapture in the conventional tags database by region of the Atlantic where they were tagged.

	At recapture		
At release	***Juv1***	***Juv2***	***Mat***
East			
Juv1	424	73	8
Juv2	0	36	9
Mature	0	0	9
West			
Juv1	2743	381	106
Juv2	0	147	142
Mature	0	0	255

Table 6. Recapture locations (columns) by release area (rows) for conventionally tagged Bluefin tuna.

	Recapture area											
Release area	***CAR***	***E_ATL***	***E_MED***	***GOM***	***GSL***	***NC_ATL***	***NE_ATL***	***SC_ATL***	***SE_ATL***	***W_ATL***	***W_MED***	***Sum***
CAR	0	3	0	3	0	0	6	0	0	6	0	18
E_ATL	0	309	0	0	0	0	2	0	11	17	13	352
E_MED	0	0	0	0	0	0	0	0	0	0	1	1
GOM	0	1	0	1	0	0	0	0	1	0	0	3
GSL	0	0	0	0	2	0	0	0	1	2	0	5
SC_ATL	0	0	0	0	0	0	0	0	0	1	0	1
SE_ATL	0	10	1	0	1	0	0	0	67	2	22	103
W_ATL	4	102	1	27	9	9	9	3	30	4393	49	4636
W_MED	0	17	3	0	0	0	0	0	10	0	196	226
Total												5345

Table 7. The probability of an area being the next one occupied and the mean sojourn time in days are given for each level of the season covariate. The mean sojourn in area *r* is given by $-1/q_{rr}$ and the intensity of a transition from area *r* to *s* is given as q_{rs} while their product ($-q_{rs}/q_{rr}$) represents the probability of state *s* being next.

From\To	W_ATL	MED	SE_ATL	NE_ATL	C_ATL	CAR	GSL	GOM	Sojourn	SE	L95%	U95%
Winter (NDJF)												
W_ATL	0	0	0	0	0	0.61	0.39	0	2.43	0.86	1.21	4.88
MED	0	0	1	0	0	0	0	0	375.63	125.88	194.76	724.47
SE_ATL	0	0.18	0	0.65	0.18	0	0	0	43.78	11.15	26.57	72.13
NE_ATL	0	0	0.67	0	0.33	0	0	0	37.76	8.76	23.96	59.51
C_ATL	0.39	0	0.26	0.36	0	0	0	0	17.71	4.21	11.12	28.2
CAR	0.99	0	0	0	0	0	0	0.01	0.75	0.2	0.45	1.25
GSL	1	0	0	0	0	0	0	0	0.21	0.16	0.05	0.93
GOM	0	0	0	0	0	1	0	0	113.71	37.94	59.12	218.68
Spring (MAMJ)												
From\To	**W_ATL**	**MED**	**SE_ATL**	**NE_ATL**	**C_ATL**	**CAR**	**GSL**	**GOM**	**Sojourn**	**SE**	**L**	**U**
W_ATL	0	0	0	0	0.07	0.63	0.3	0	36.26	10.61	20.43	64.36
MED	0	0	1	0	0	0	0	0	228.76	72.43	122.99	425.49
SE_ATL	0	0.74	0	0.19	0.07	0	0	0	19.6	2.54	15.2	25.26
NE_ATL	0	0	0.79	0	0.21	0	0	0	84.85	29.01	43.41	165.86
C_ATL	0.51	0	0.21	0.27	0	0	0	0	19.44	4.23	12.69	29.77
CAR	0.89	0	0	0	0	0	0	0.11	4.88	0.77	3.58	6.64
GSL	1	0	0	0	0	0	0	0	1.6	1.13	0.4	6.36
GOM	0	0	0	0	0	1	0	0	44.82	7.44	32.38	62.05
Summer/Fall (JASO)												
From\To	**W_ATL**	**MED**	**SE_ATL**	**NE_ATL**	**C_ATL**	**CAR**	**GSL**	**GOM**	**Sojourn**	**SE**	**L**	**U**
W_ATL	0	0	0	0	0	0	1	0	1.59	0.59	0.76	3.31
MED	0	0	1	0	0	0	0	0	38.26	11.89	20.8	70.37
SE_ATL	0	0.77	0	0.22	0.01	0	0	0	6.23	1.45	3.95	9.83
NE_ATL	0	0	0.54	0	0.46	0	0	0	287.97	84.85	161.64	513.04
C_ATL	0.66	0	0.22	0.12	0	0	0	0	25.13	8.25	13.21	47.82
CAR	0.64	0	0	0	0	0	0	0.36	2.42	2	0.48	12.24
GSL	1	0	0	0	0	0	0	0	0.42	0.15	0.21	0.83
GOM	0	0	0	0	0	1	0	0	5.89	11.15	0.14	240.53

Table 8. The passage probabilities are the probability that each area will be visited within a specified length of time (365 days). Covariates were set to the mean level.

From\To	W_ATL	MED	SE_ATL	NE_ATL	C_ATL	CAR	GSL	GOM
W_ATL	1	0.04	0.07	0.06	0.19	0.9	1	0.22
MED	0.17	1	0.96	0.61	0.3	0.1	0.17	0.02
SE_ATL	0.24	0.8	1	0.73	0.41	0.15	0.24	0.03
NE_ATL	0.32	0.56	0.75	1	0.53	0.22	0.32	0.04
C_ATL	0.67	0.33	0.43	0.41	1	0.56	0.67	0.13
CAR	1	0.04	0.06	0.06	0.19	1	1	0.29
GSL	1	0.04	0.07	0.06	0.19	0.9	1	0.21
GOM	1	0.04	0.06	0.06	0.18	1	1	1

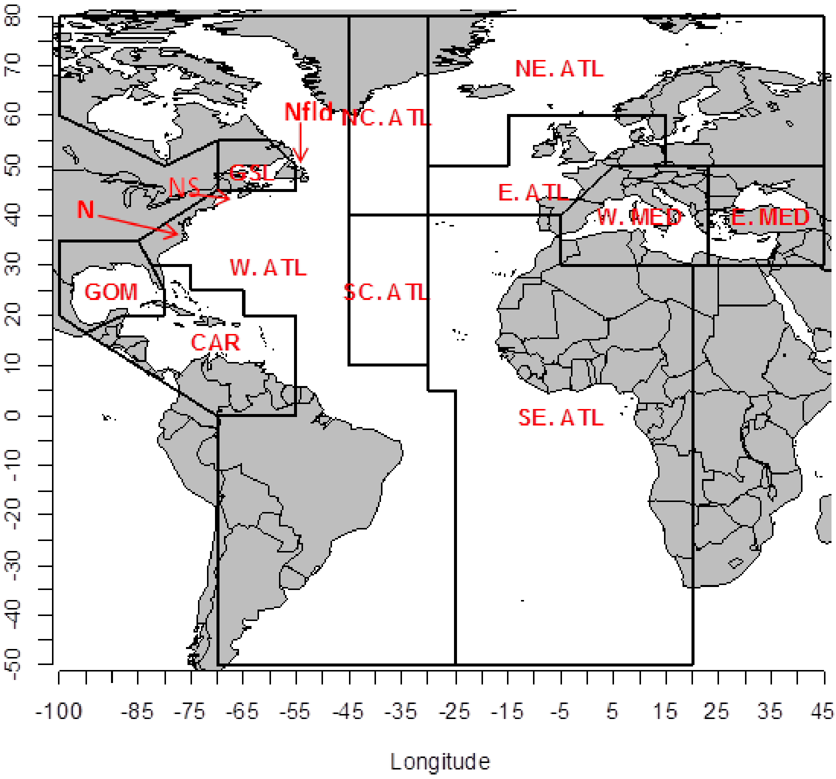


Figure 1. The map indicates the broad geographic areas used to aggregate the conventional and etag data. NS= Nova Scotia; Nfld=Newfoundland; N=North Carolina.

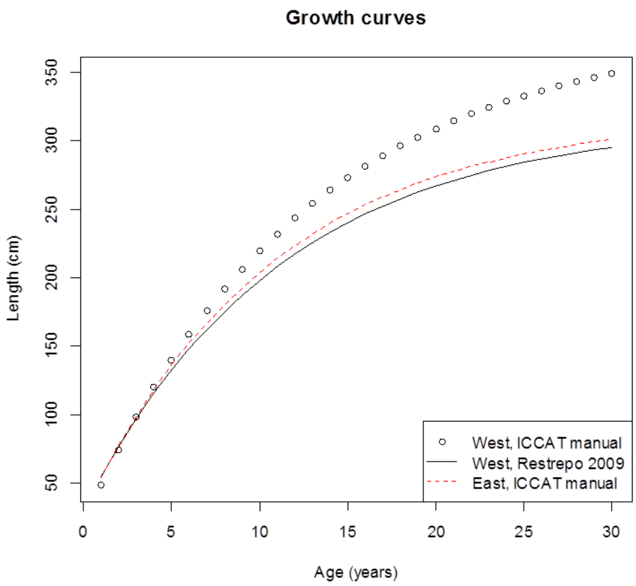


Figure 2. Eastern and western Bluefin tuna growth curves from the ICCAT manual and the recent western Bluefin tuna update by Restrepo *et al.* 2009, suggesting that eastern and western fish have similar growth rates.

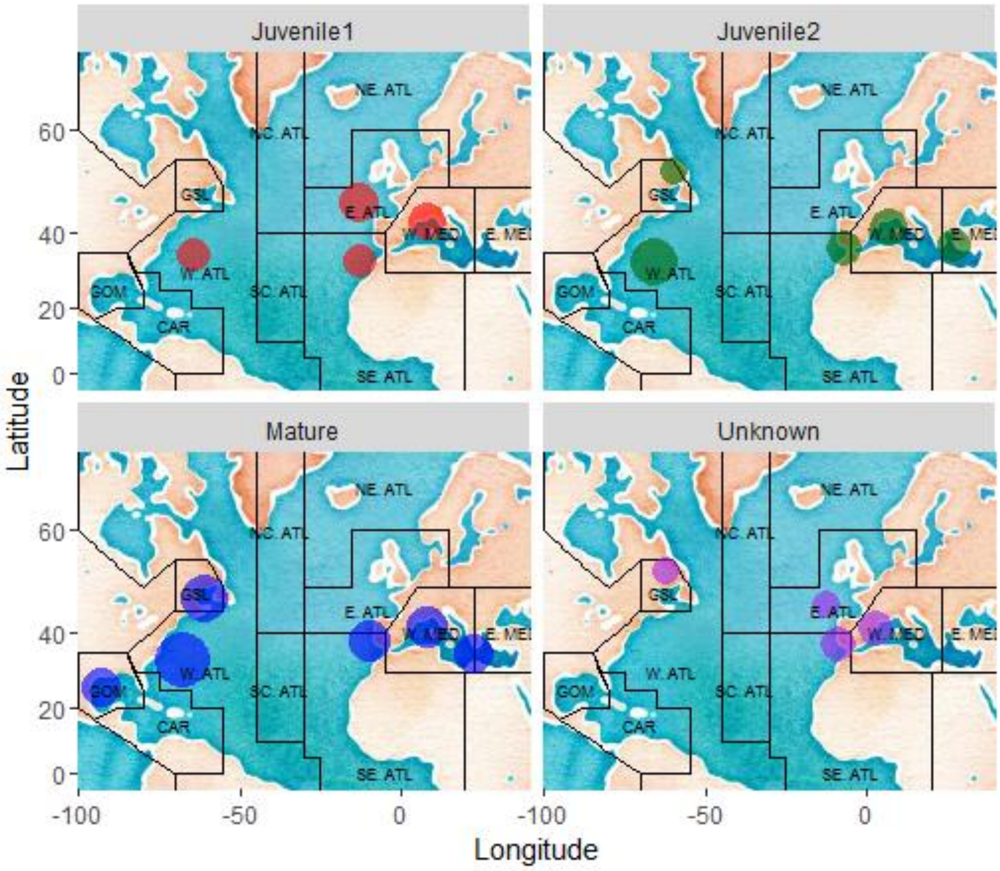


Figure 3. Deployment area of tagged Bluefin tuna by maturity class where point size scales with number of deployments. Fish greater than 187 cm or 129 kg are Mature, those less than 115 cm and 31 kg are Juvenile1 and fish of intermediate size are Juvenile2.

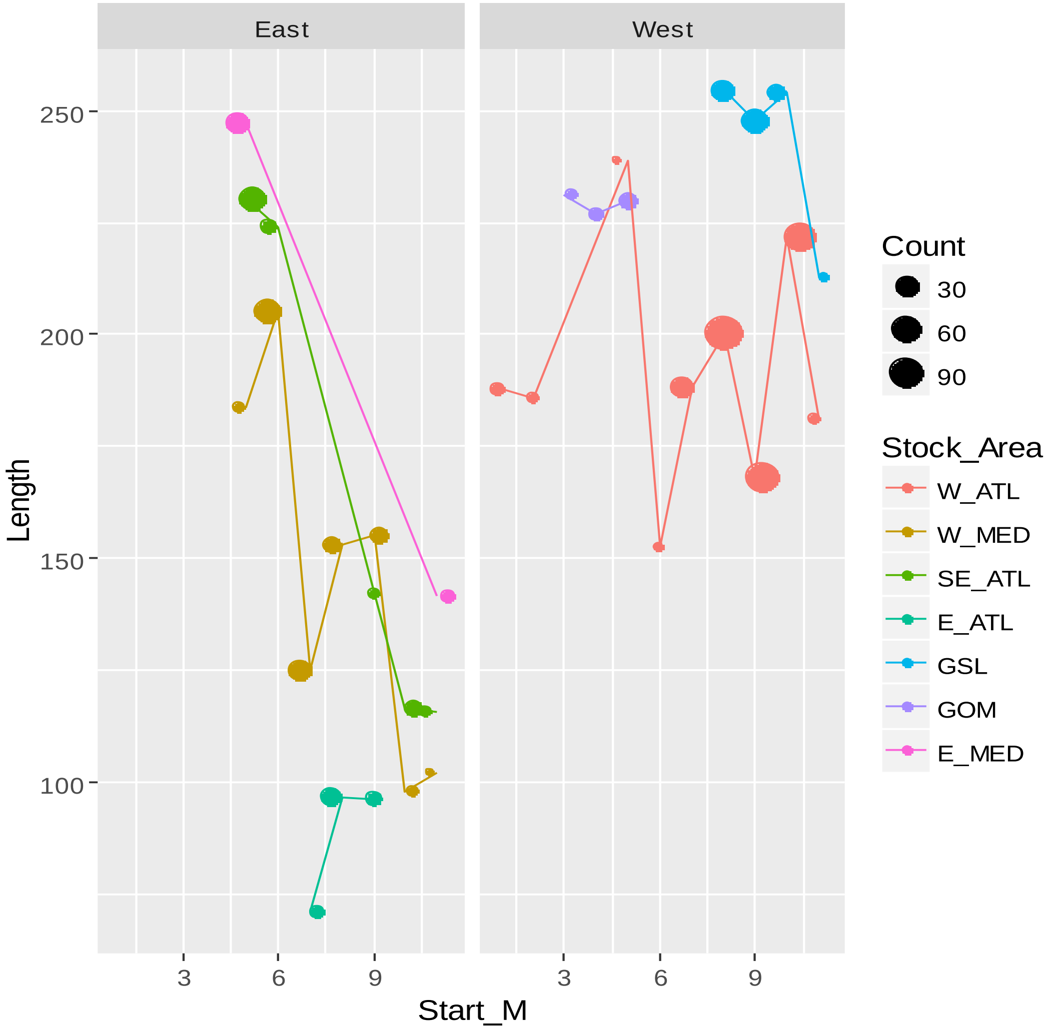


Figure 4. Mean length (cm) of Bluefin tuna at tag deployment by deployment area, management zone and month. Size of point scales with number of tags in sample.

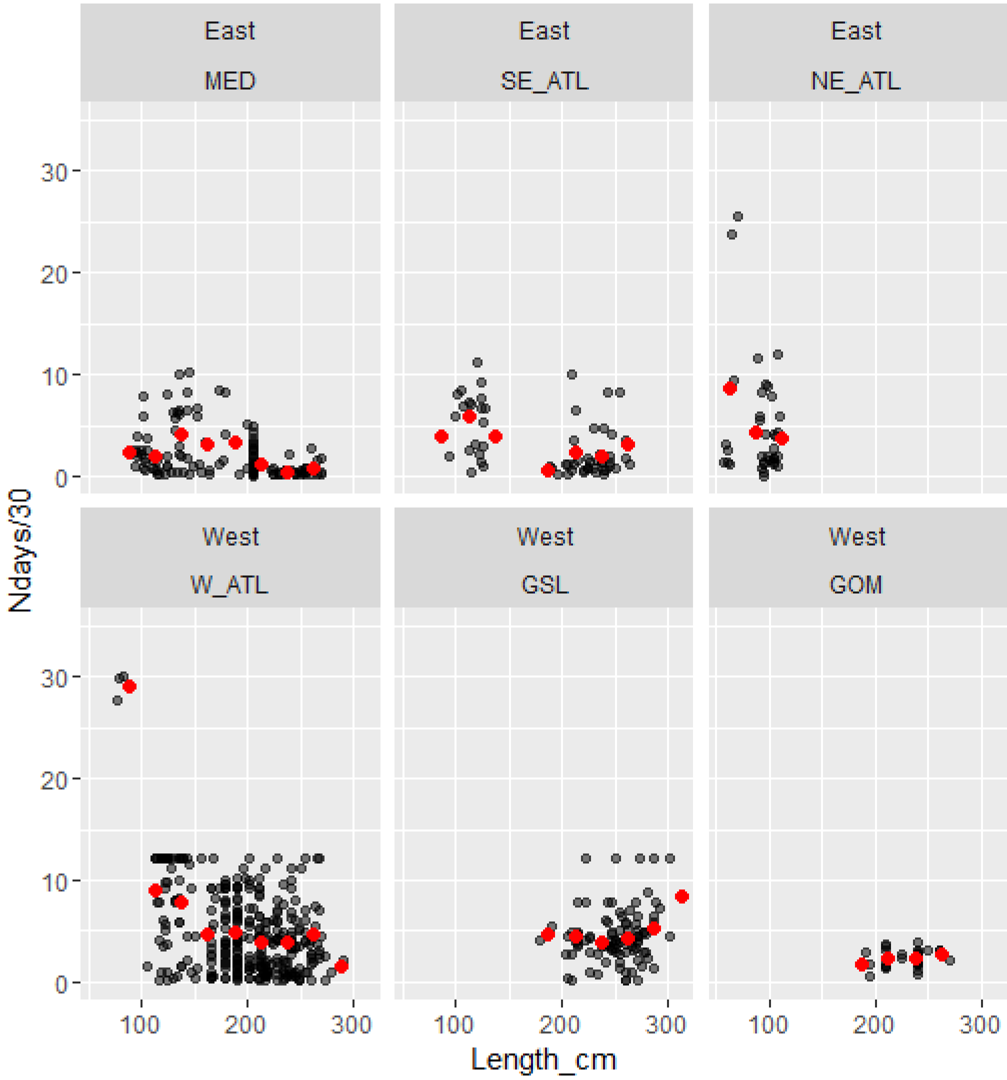


Figure 5. Months at large relative to the deployment length of Bluefin tuna by management zone and tagging area. Individual fish are shown in black and mean deployment length by 25 cm bins is in red. The long deployments on small fish are archival rather than PSAT tags. Note that NE_ATL is a combination of Eastern and North Eastern areas and MED is both Mediterranean areas combined.

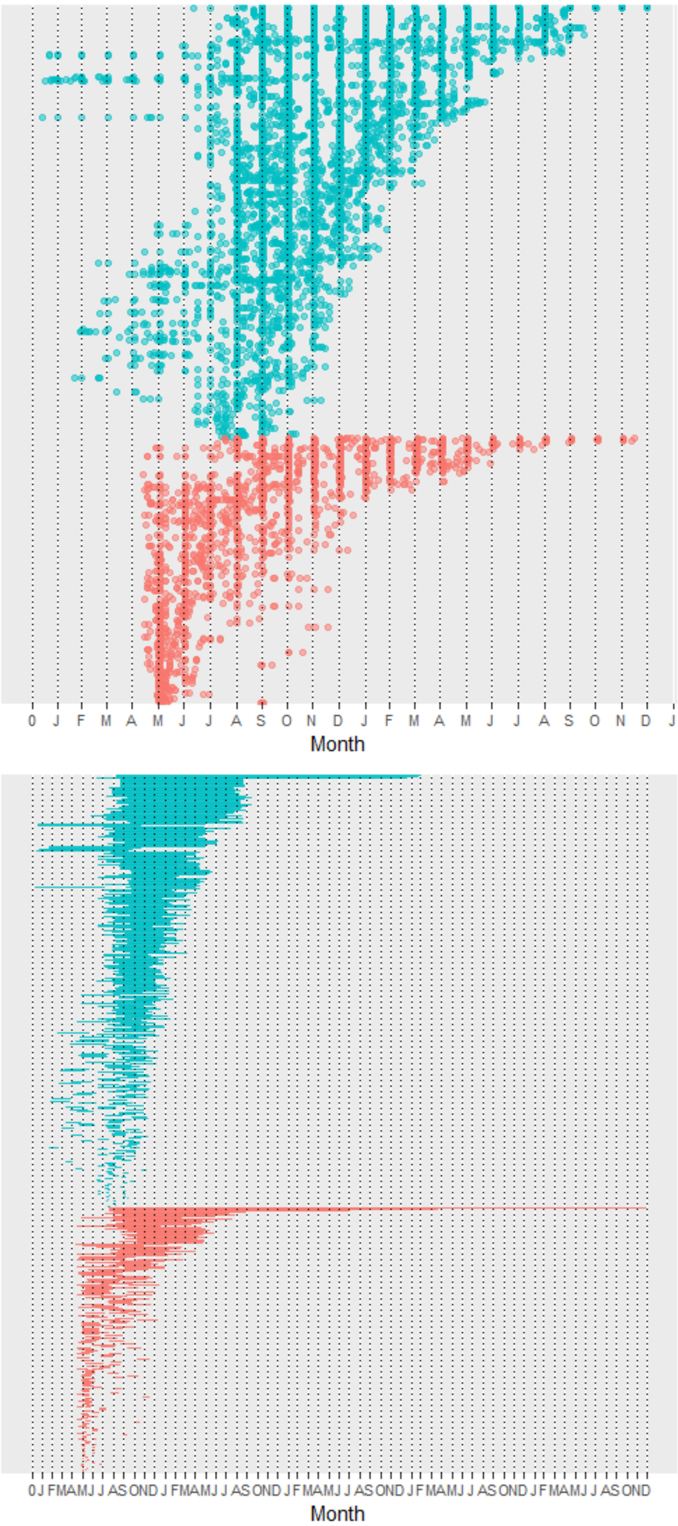


Figure 6. Timing and duration of tag deployments by management zone (red= East, blue=West). Note that the duration is truncated in the upper plot while the lower plot shows the full duration of tag deployments. Deployments longer than one year are likely internal archival tags. The deployments are arranged from shortest to longest duration within each zone. The points in the upper plot indicate both when a Bluefin tuna remains in the same area for consecutive months (point falls on dotted line) and a change in area (point falls between dotted lines).

Figure 7. Sojourn times and percentages for Bluefin tuna tagged in the eastern and western management zones. The average sojourn time by area is shown in red.

Figure 8. Percent sojourn of tagged Bluefin tuna in each stock area relative to the deployment area (panels). Average percent is given in red. For example, deployments in the Gulf of Mexico resulted in sojourns in the Western Atlantic, Caribbean, Gulf of St. Lawrence and Gulf of Mexico.

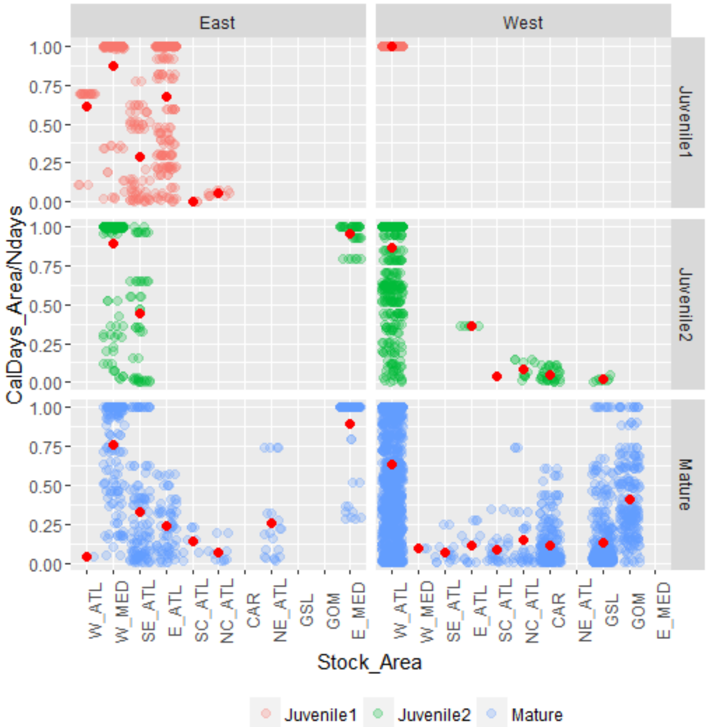


Figure 9. The percentage sojourn time for juvenile and mature Bluefin tuna tagged within the eastern and western management zone. The average percentages are in red. Fish greater than 187 cm or 129 kg are Mature, those less than 115 cm and 31 kg are Juvenile1 and fish of intermediate size are Juvenile2.

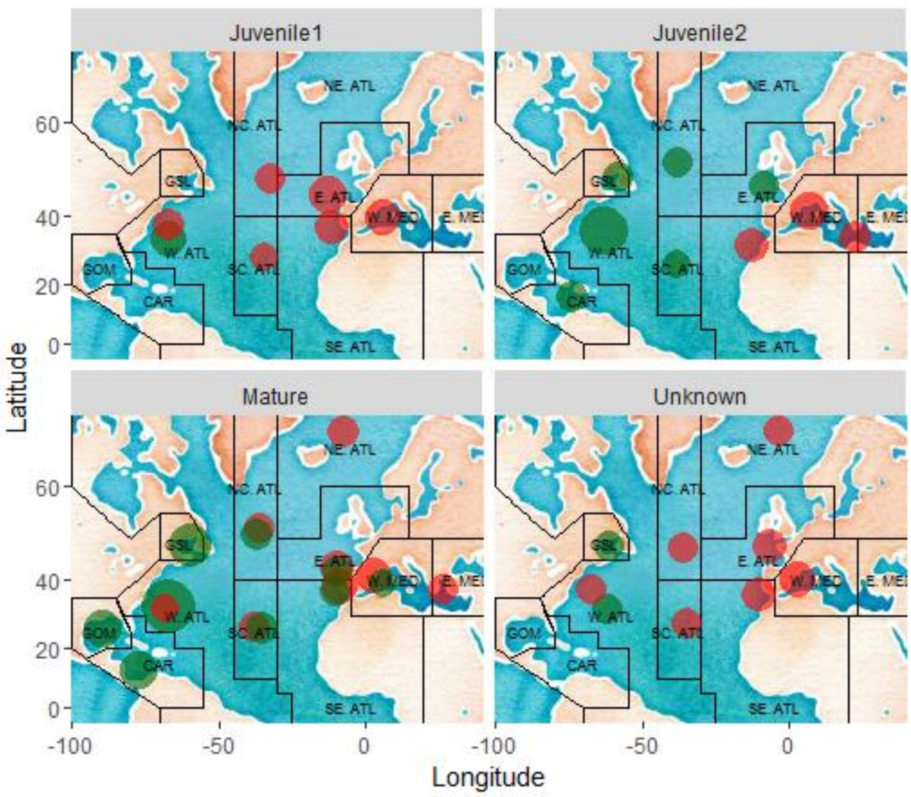


Figure 10. Transit areas of tagged Bluefin tuna by zone of deployment (red=East, green=west) and maturity class where deployment length was greater than 30 days. Fish greater than 187 cm or 129 kg are Mature, those less than 115 cm and 31 kg are Juvenile1 and fish of intermediate size are Juvenile2.

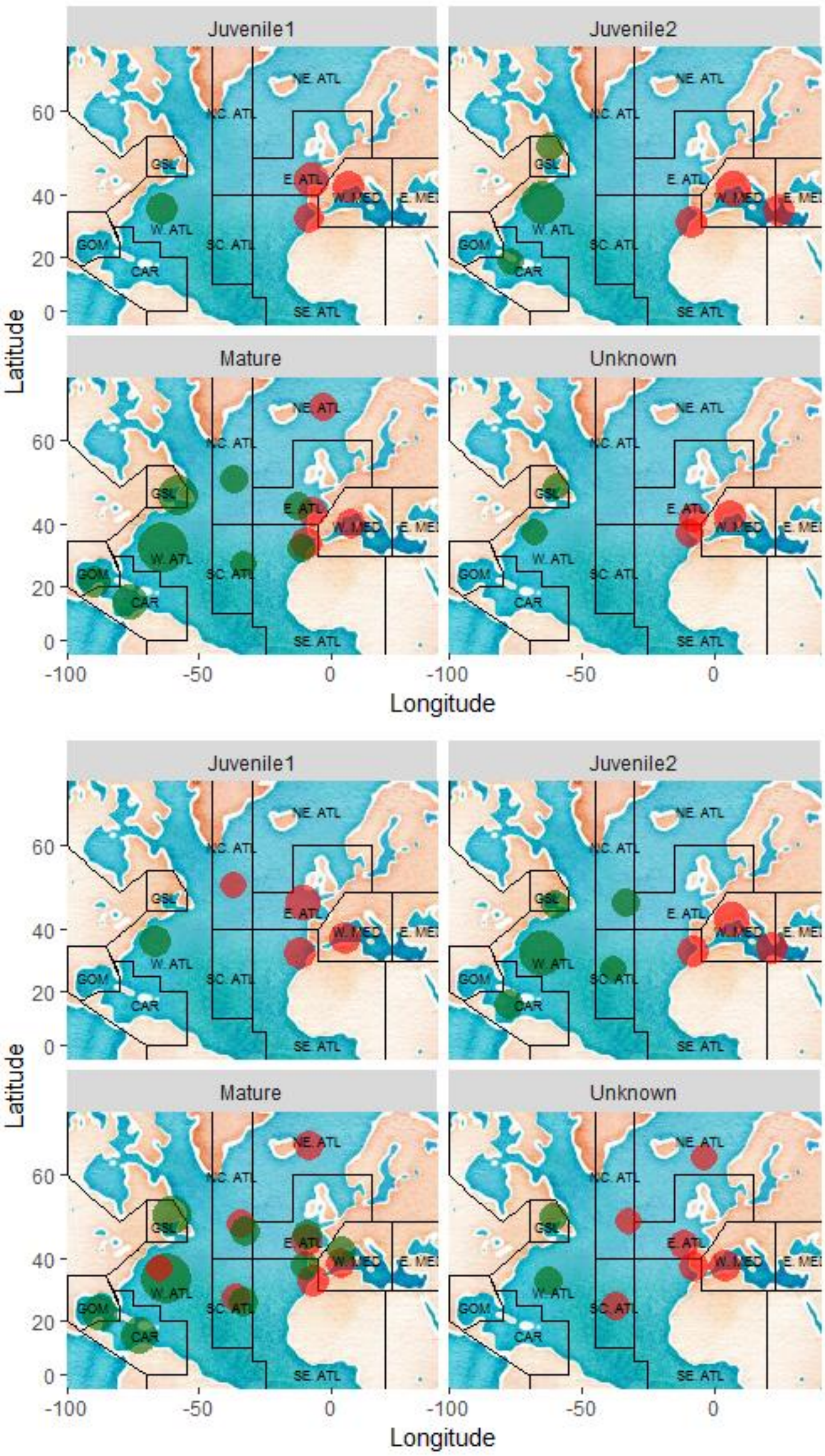


Figure 11. Transit areas of tagged Bluefin tuna by zone of deployment (red=East, green=west) and maturity class. Days at liberty was greater than 30 days but less than 120 (West 160 and East 105 tags) (top panels) and greater than 30 days but less than 230 (West 281 and East 143 tags) (bottom panels). Fish greater than 187 cm or 129 kg are Mature, those less than 115 cm and 31 kg are Juvenile1 and fish of intermediate size are Juvenile2.

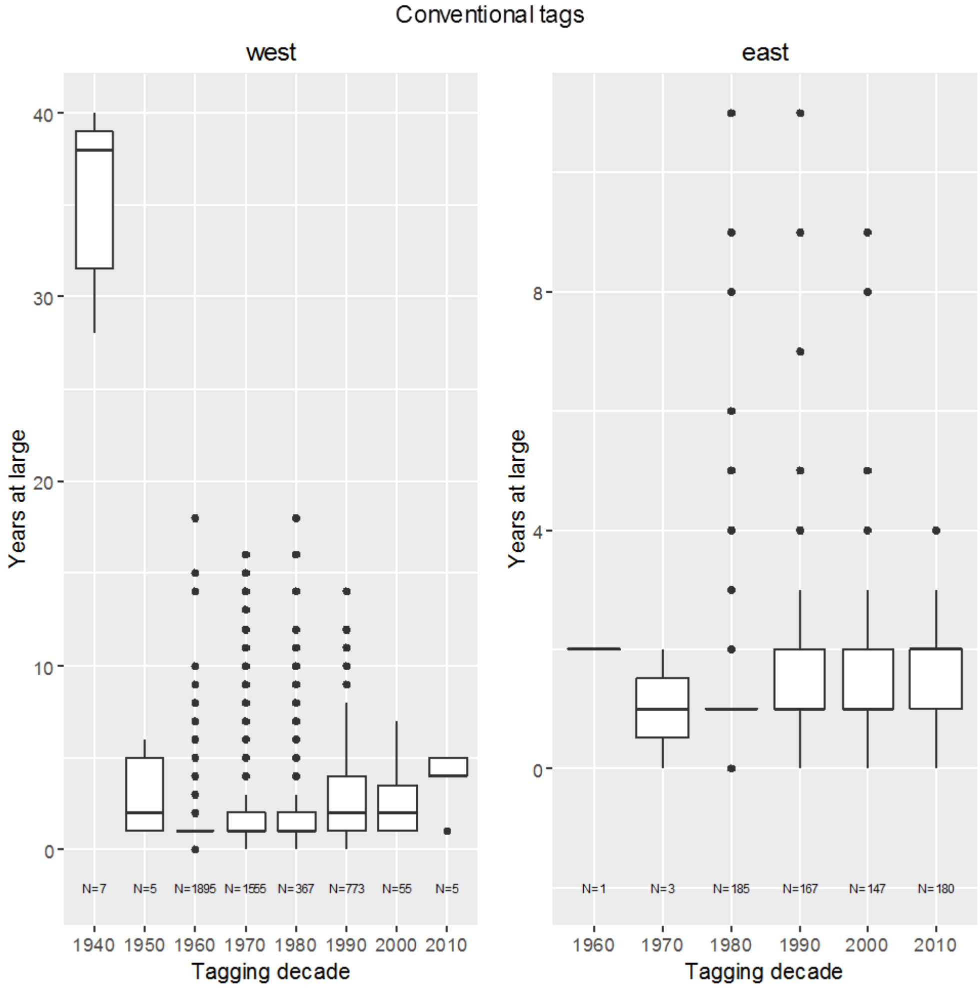


Figure 12. Years at large for fish tagged using conventional tags as available in the ICCAT database.

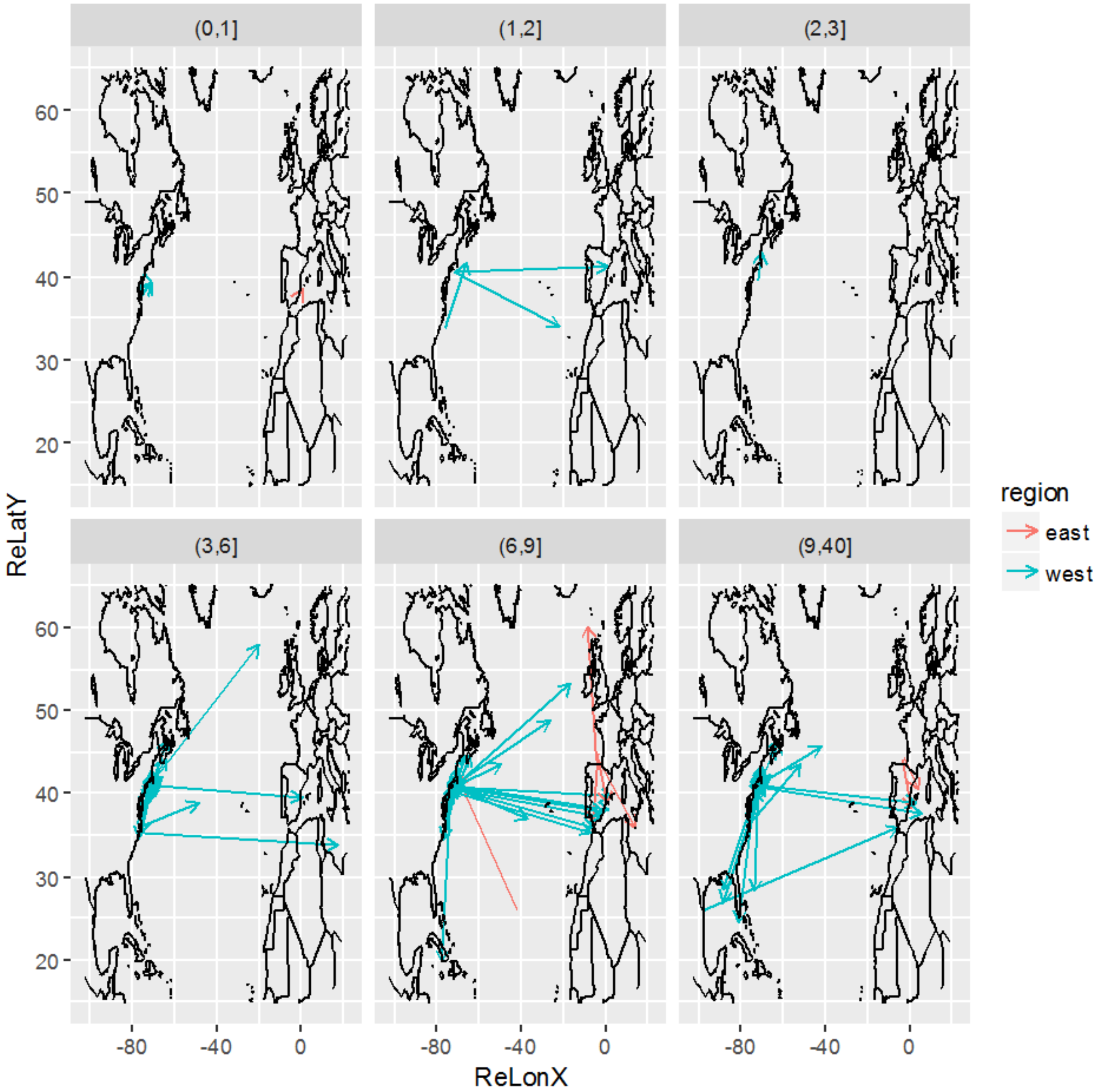


Figure 13. Capture and recapture locations for conventionally tagged Bluefin tuna which were in the Juvenile1 size class at capture and the Mature size class at recapture. Panels reflect years at large. The label (0,1] reflects the first year at large, for example.

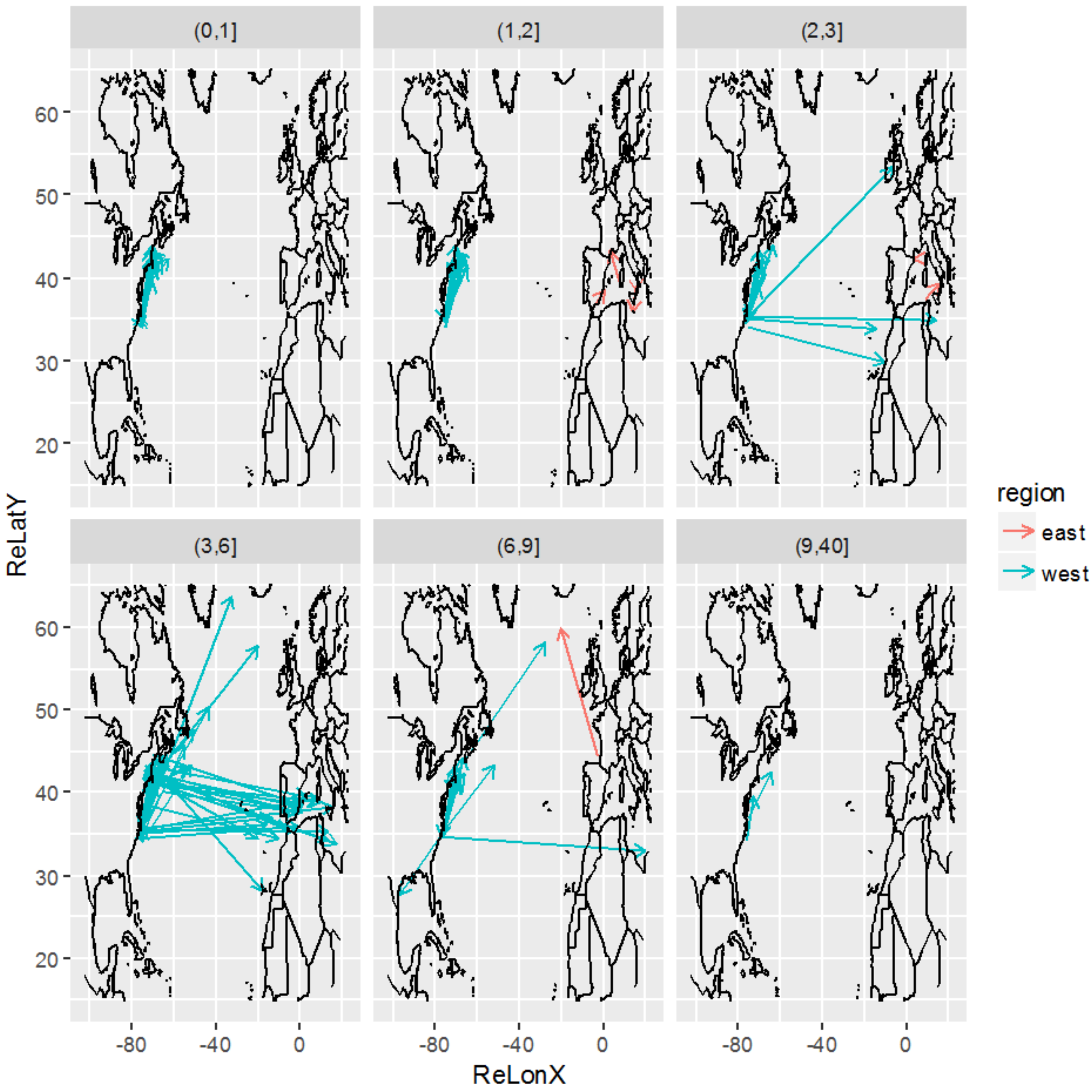


Figure 14. Capture and recapture locations for conventionally tagged Bluefin tuna which were in the Juvenile2 size class at capture and the Mature size class at recapture. Panels reflect years at large. The label (0,1] reflects the first year at large, for example. Recaptures after less than 1 month at large were excluded.

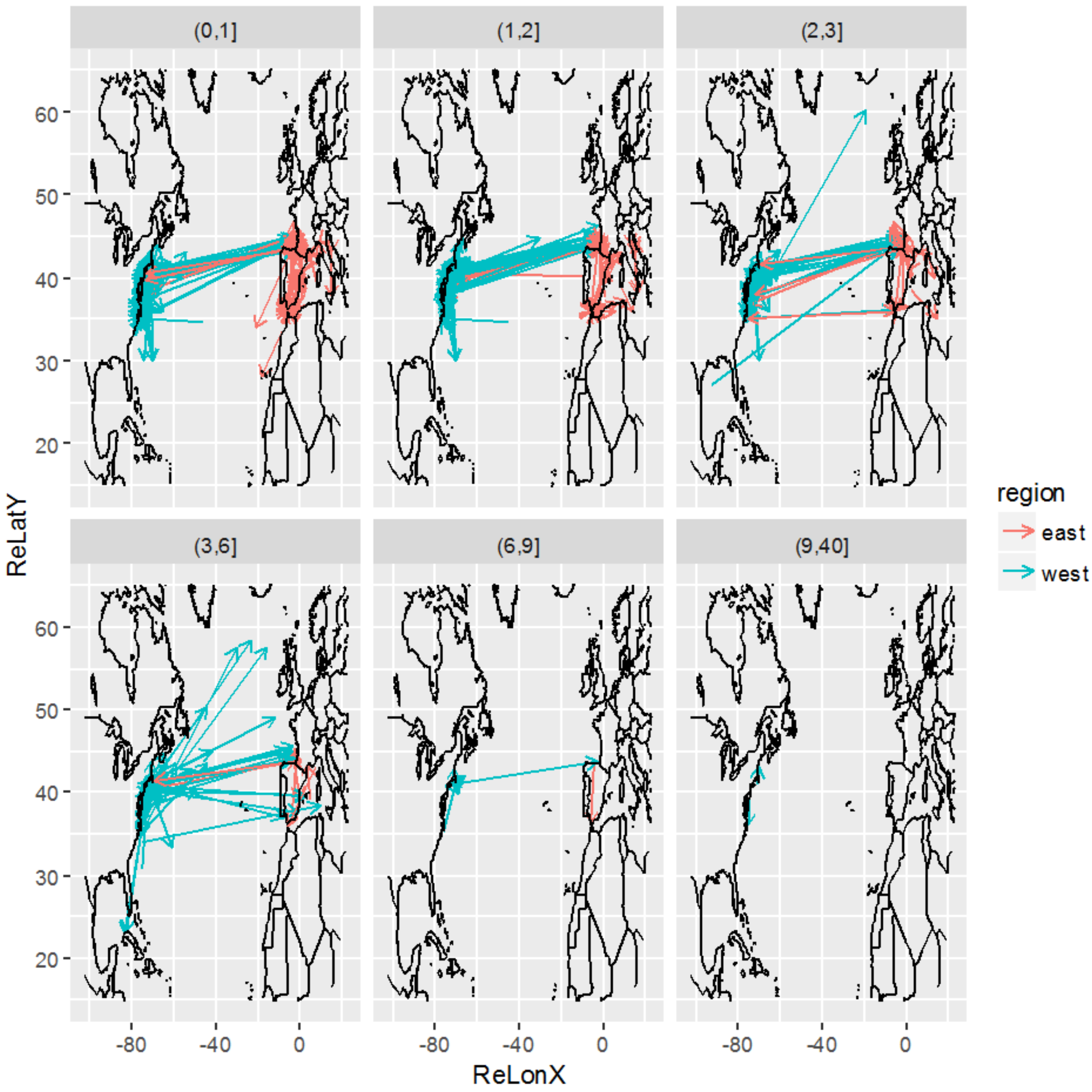


Figure 15. Capture and recapture locations for conventionally tagged Bluefin tuna which were in the Juvenile size class both at capture and at recapture. Panels reflect years at large. The label (0,1] reflects the first year at large, for example. Recaptures after less than 1 month at large were excluded.

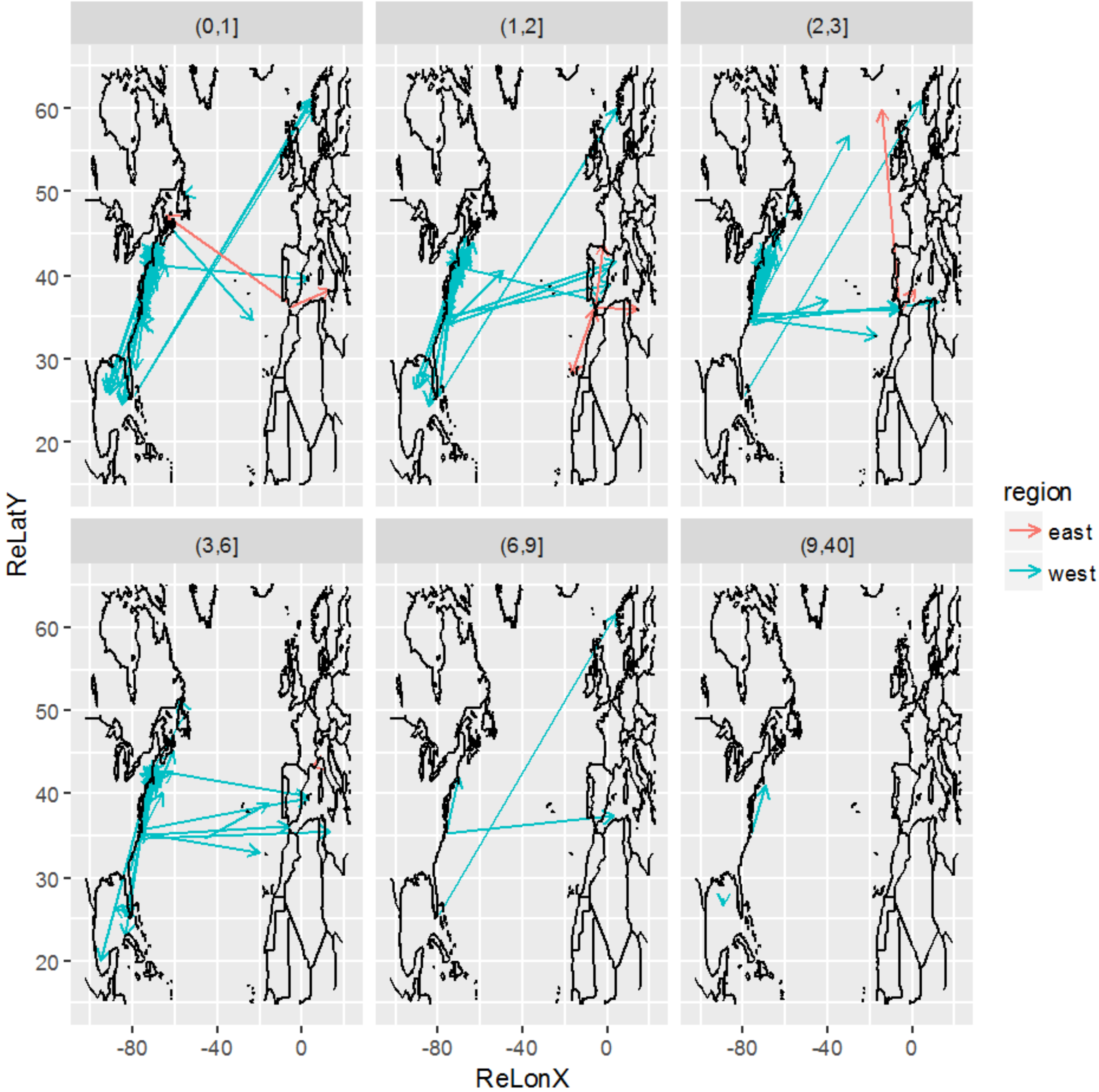


Figure 16. Capture and recapture locations for conventionally tagged Bluefin tuna which were in the Mature size class at capture and at recapture. Panels reflect years at large. The label (0,1] reflects the first year at large, for example. Recaptures after less than 1 month at large were excluded.

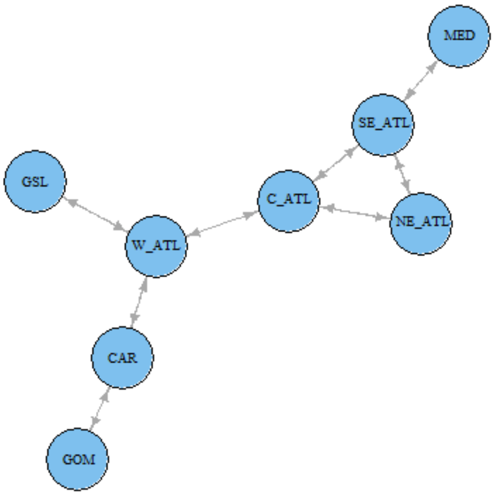


Figure 17. A directed digraph for the initial transition intensity matrix of a multi-state Markov model describing the movement of Bluefin tuna through marine areas in continuous time. Movements are constrained to pass through adjacent areas.

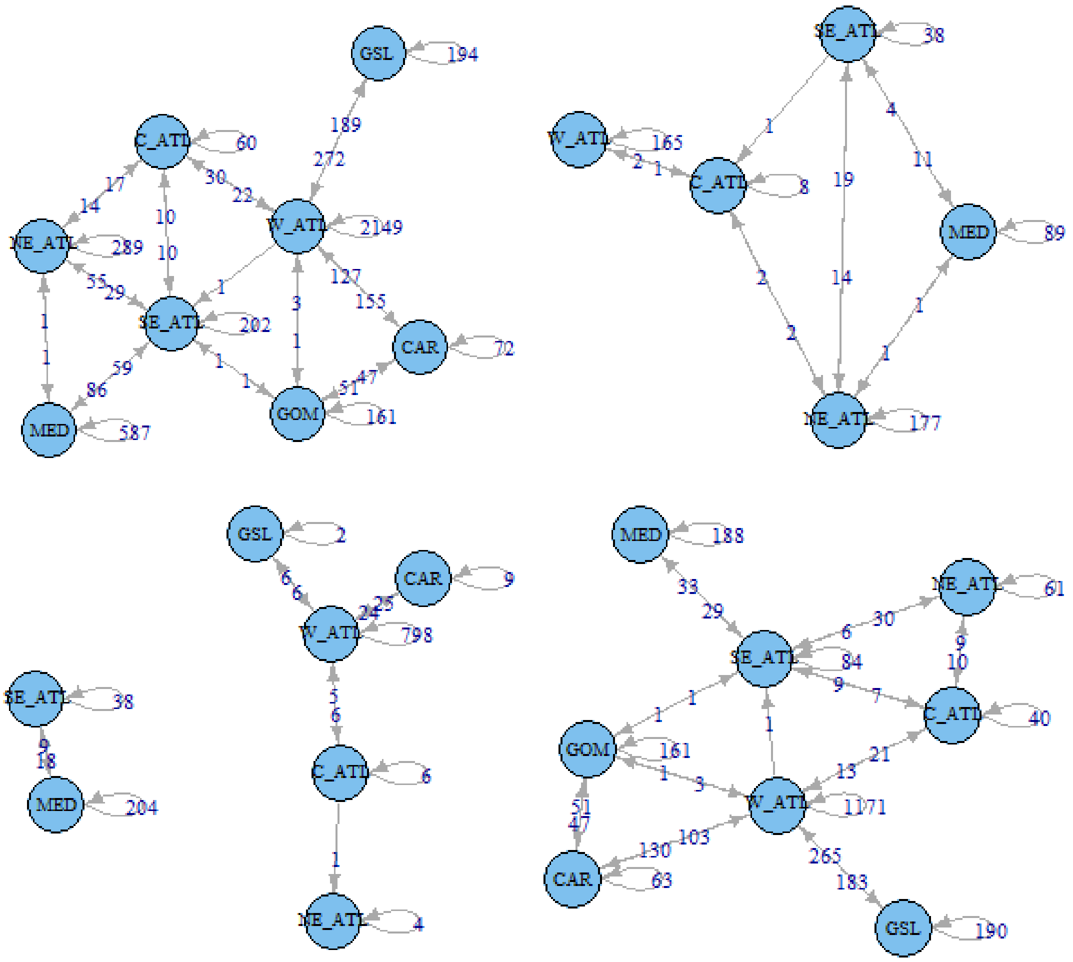


Figure 18. Directed digraphs based on the frequency of transitions between areas for 1) all etagged fish (top left), 2) Juvenile1 sized fish (top right), 3) Juvenile2 sized fish (bottom left) and 4) Mature sized fish (bottom right). Transitions occur on a regular monthly time step.

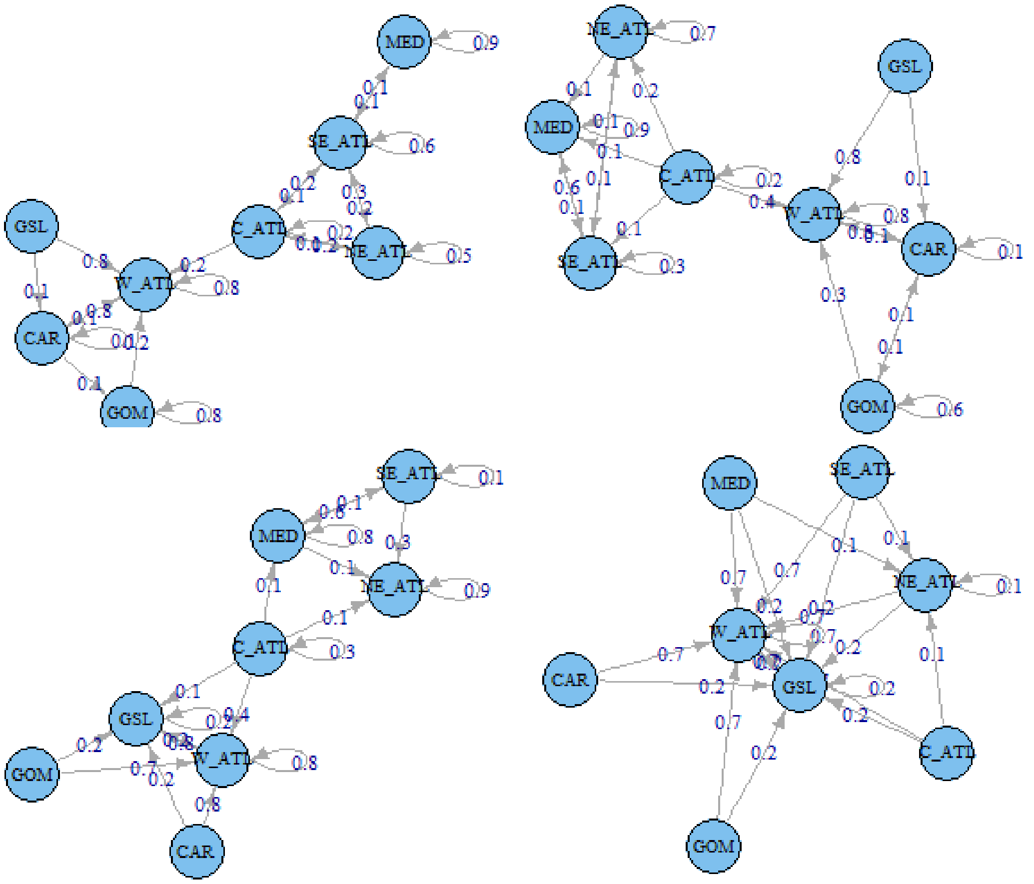


Figure 19. Directed digraphs for transition probability matrices estimated using a multi-state continuous time Markov model based on data from 722 Bluefin tuna etags. Digraphs are shown for each level of the covariate season and with the covariate set to zero. Top left: season = NDJF, Top right: season = MAMJ, Bottom left: season = JASO and Bottom right: Covariates set to zero. The time interval to estimate the transition probabilities for was set to 30 days for all digraphs except the bottom right which was set to 3600 days.

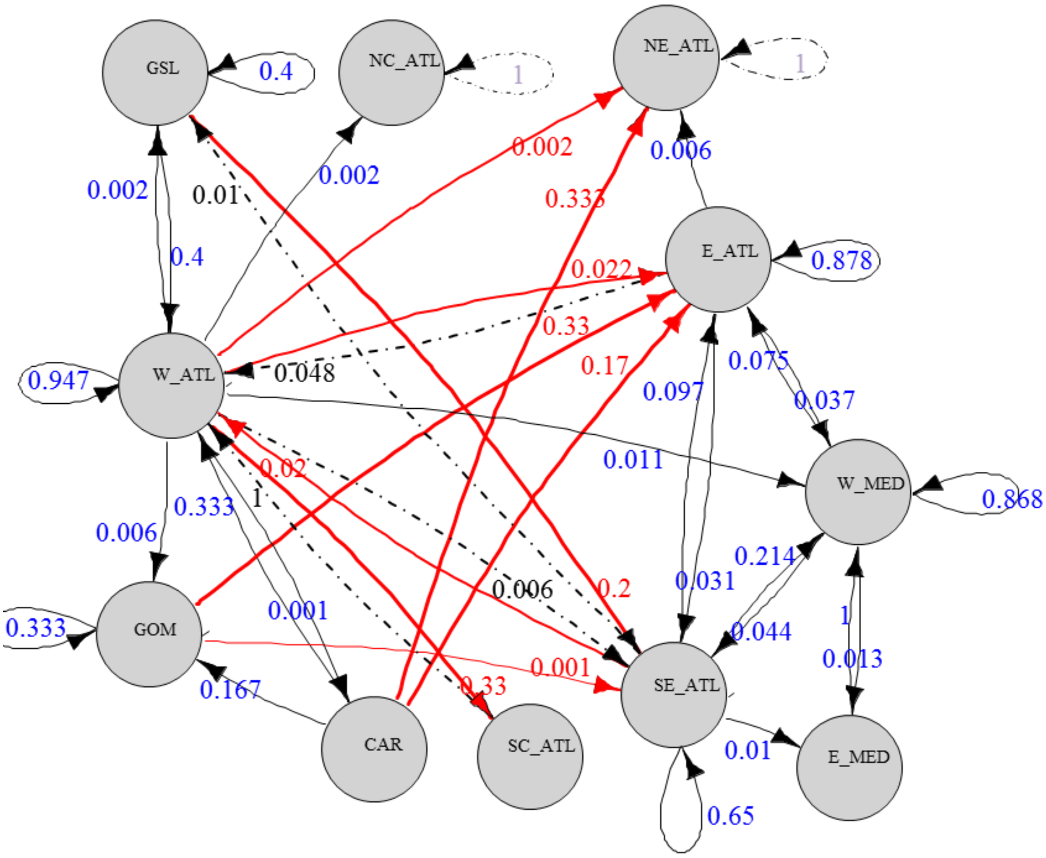
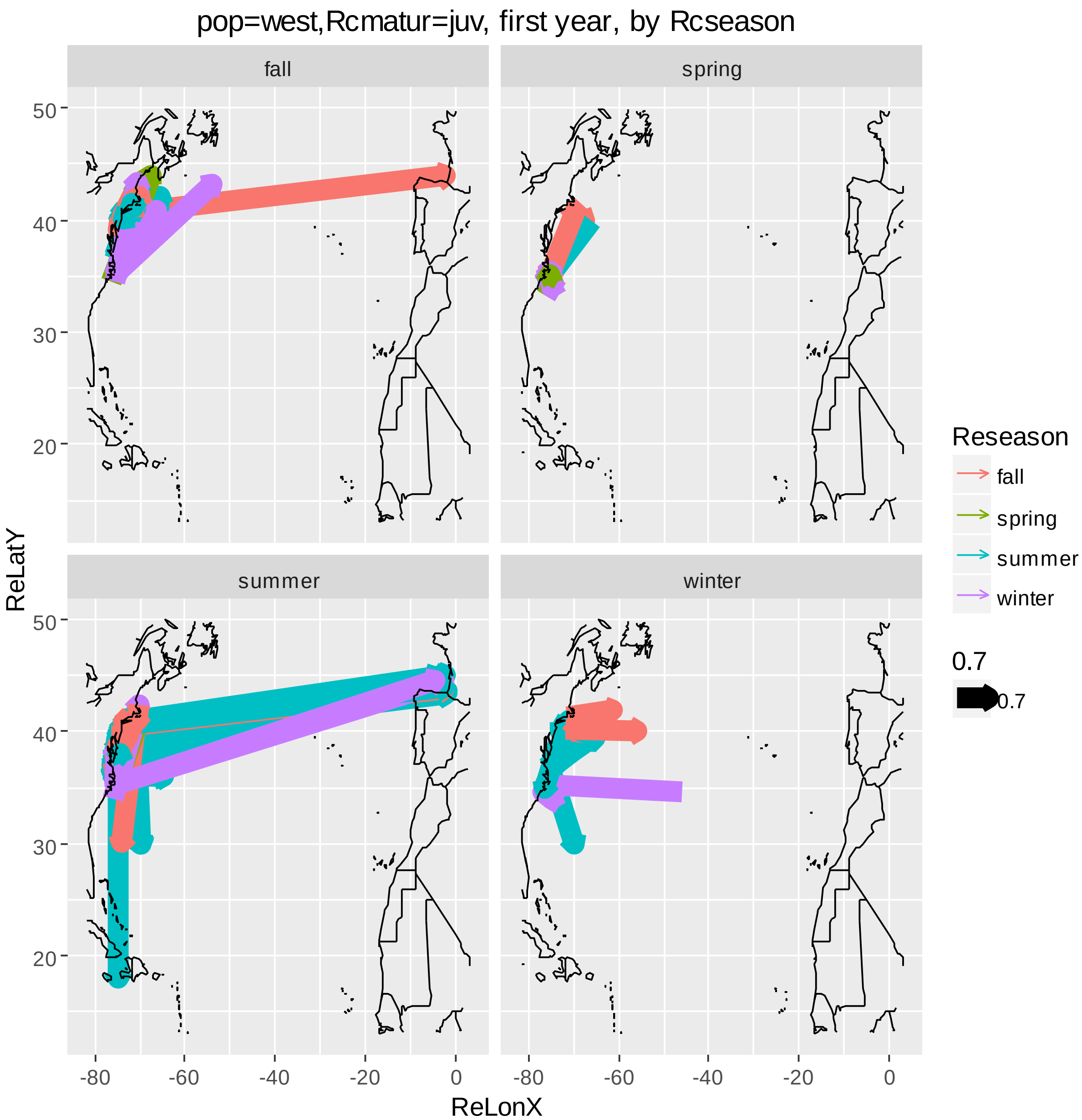
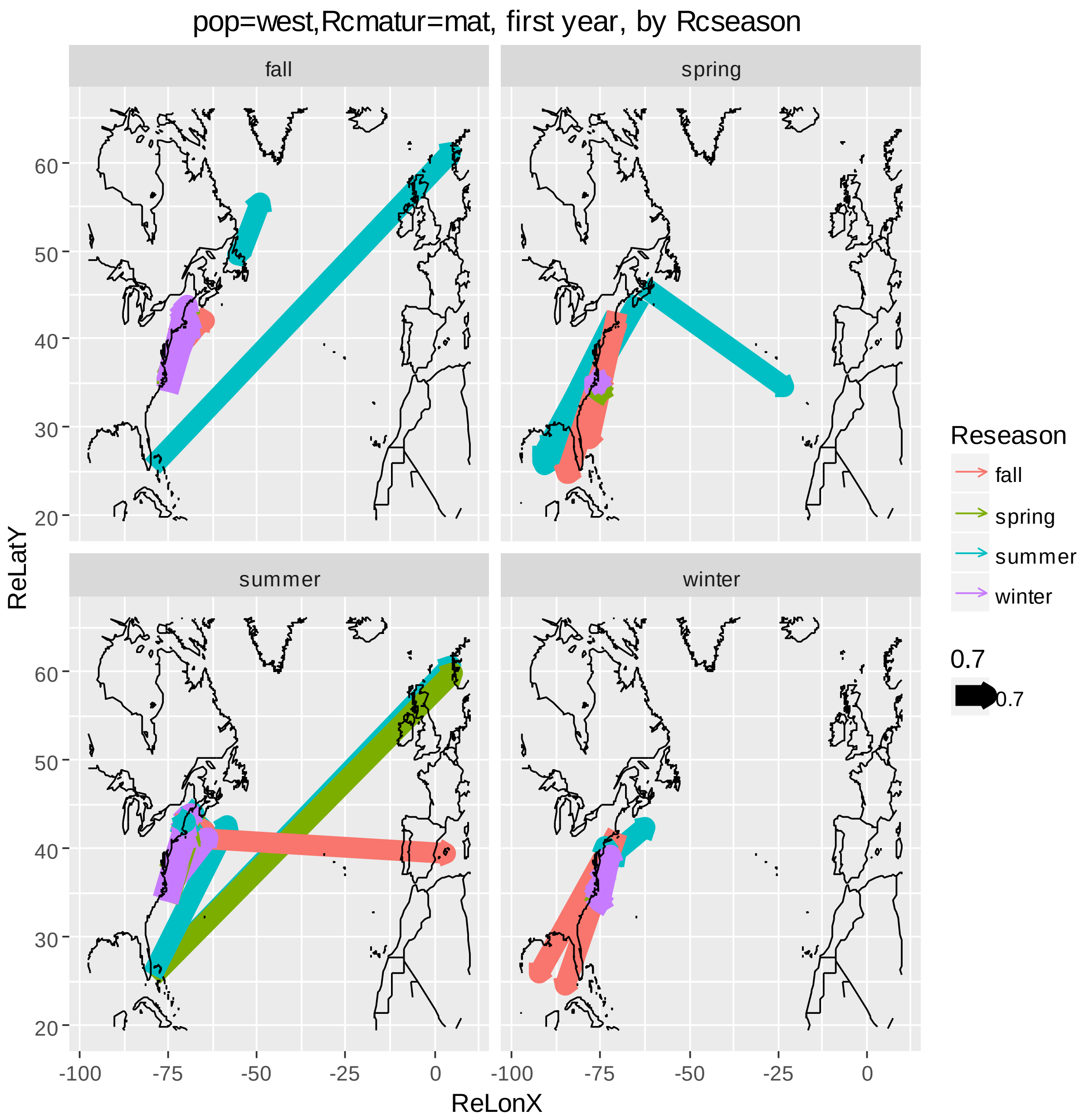


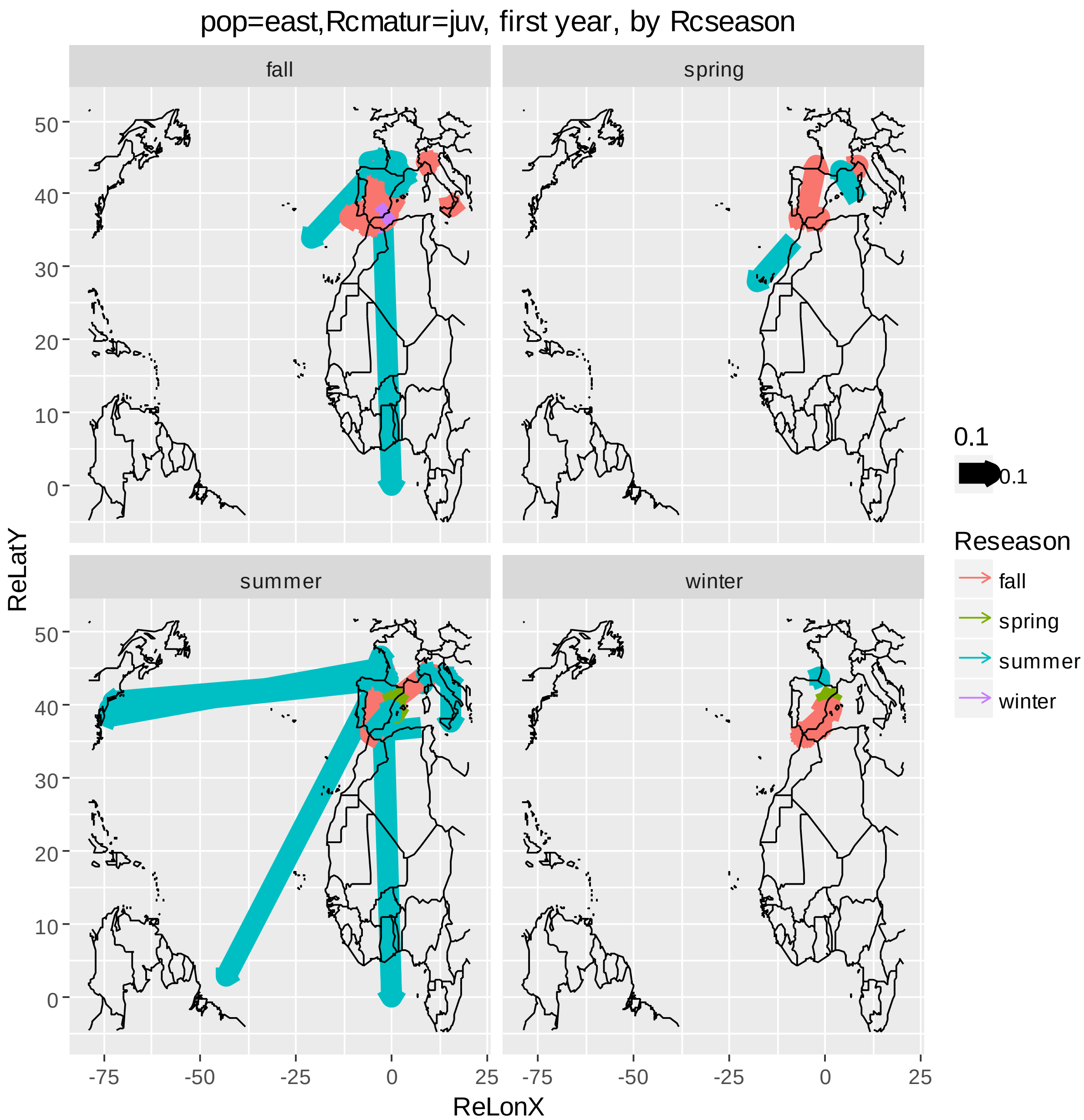
Figure 20. A directed digraph of transition probabilities estimated from the conventional tag data. Thick red lines show the migrations from West to East; the stippled lines show the migrations from East to West. Note that the digraph represents transitions for all size classes of tuna and with no consistent transition interval.

Bluefin Tuna Conventional Tagging, Movements in the First Year At Large by Season of Capture and Recapture, Management Zone and Maturity Class



Prefix Rc = recapture and Re = release.


pop=west,Rcmatur=mat, first year, by Rcseason
fall
spring
summer
winter
ReLatY
ReLonX
60
50
40
30
20
-100
-75
-50
-25
0
Reseason
fall
spring
summer
winter
0.7
0.7


pop=east,Rcmatur=juv, first year, by Rcseason
fall
spring
summer
winter
ReLatY
50
40
30
20
10
0
-75
-50
-25
0
25
ReLonX
0.1
0.1
Reseason
fall
spring
summer
winter