Differences in large-scale movement between free swimming and fish aggregating device (FAD) caught tuna

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Abstract

Tropical tuna are amongst a number of pelagic fish species that are known to aggregate around floating objects. While the ecological or evolutionary advantage of this behaviour is still unclear, tuna fishermen have been exploiting it for decades by actively seeding artificial FADs, modifying the physical habitat of tuna. There are growing concerns over the ecological impact of this phenomenon, especially the potential of FADs to act as an ecological trap. We used the Indian Ocean Tuna Commission mark recapture database to determine whether there are differences in movement characteristics between tuna caught in free schools and those caught under FADs that might be indicative of an impact of FADs on large-scale tuna movement. We found that there were some differences in displacement rates between individuals caught at FADs and those caught in free-swimming schools, as well as differences in movement angles. We suggest, however, that this is not necessarily an indication of a FAD effect on tuna movement, but might be an artefact of the non-uniform distribution of FAD fishing effort. We furthermore show that movement characteristics did not differ between fish tagged during periods of high and those tagged during periods of low FAD density and suggest that this might indicate the absence of an ecological trap effect. We conclude that school type at recapture might not be representative of a tuna's movement history and therefore not suitable for detecting an ecological trap effect of FADs. Hence we propose the use of a more sophisticated statistical model of the mark-recapture data to address the question of whether FADs have the potential to alter large-scale tuna movements.

Introduction

Tropical tuna such as bigeye (*Thunnus obesus*), skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares*) are amongst a number of pelagic fish species that are known to aggregate around floating objects (Castro et al. 2002). While the ecological or evolutionary advantage of this behaviour is still unclear (Dempster & Taquet 2004), tuna fishermen have known of and been exploiting it for decades - originally by fishing around natural floating objects such as logs mainly in the vicinity of mangroves or estuaries of large rivers and since the 1980s by actively seeding artificial fish aggregating devices (FADs) (Fonteneau et al. 2000; Fréon & Dagorn 2000), most of which consist of a bamboo raft with attached fishing nets hanging down to a depth of up to 30 m. Today 75% of skipjack and 35% of yellowfin tuna catches by purse seiners in the Atlantic and Indian Ocean are taken around floating objects FADs (Hallier & Gaertner 2008). The release of large numbers of artificial FADs has led to a marked increase in the density of floating objects, especially in the Indian Ocean, where an estimated 2100 drifting objects are monitored by the purse seine fishing fleet at any given time (Moreno et al. 2007), outnumbering natural drifting objects by a factor of up to 40 in some areas (Fauvel et al. 2009).

This change in densities of floating objects through the deployment of FADs constitutes an alteration of the physical habitat of tuna and there are growing concerns over the ecological impact of this phenomenon (Marsac et al. 2000), especially the potential of FADs to act as an ecological trap. An ecological trap exists, when a rapid alteration of a species' habitat leads animals to choose low quality habitats over available habitats of higher quality with negative ecological effects (Battin 2004). Applied to the case of tuna and FADs, this means that the attraction to FADs might override environmental cues and alter the movement of tuna, leading them to low quality habitats, with potential detrimental effects on individual fitness and/or population health. While any possible detrimental effects on both the individual and the population level are difficult to determine for a highly migratory species such as tuna, impacts of an increase in floating object densities on movement patterns are more readily identifiable through the analysis of individual movement.

The aim of this study is to analyse the Indian Ocean Tuna Commission (IOTC) regional tagging database to identify differences in movement characteristics between tuna caught in free-swimming schools and those caught under FADs that might be indicative of an impact of FADs on the tuna's large-scale movement, as suggested by Hallier & Gaertner (2008).

Methods

Data set

During the IOTC regional tagging project, a total of 34,568 bigeye, 78,334 skipjack and 54,685 yellowfin tuna were tagged between May 2005 and August 2007. The three main tagging areas were off the coast of Tanzania, in the Mozambique Channel and around the Seychelles with a few additional fish tagged in the Arabian Sea and near the Maldives. By the 15th of January 2010, a total of 25,730 (5,007 bigeye, 11,812 skipjack, 8,911 yellowfin) tags had been returned with complete recapture records, including date and location of recapture. For 16,403 of the records (3,333 bigeye, 7,305 skipjack, 5,765 yellowfin) information on the school type (FAD or free) at recapture was available from logbooks; this is the dataset we used for the analyses in this study unless stated otherwise. The school type FAD in the dataset includes fish caught at both artificial and natural floating objects. Therefore, in the rest of the document, we will use the term FAD for any floating object, either natural or artificial. From the mark and recapture locations we calculated straight-line displacement in nautical miles and bearing along the rhumb line in degrees relative to true North as the zero-direction. For 14,799 of the records, the fish could not be traced back to a single set, hence displacement and bearing were calculated using the mean longitude and latitude of all sets the fish could have been captured in as the recapture location. This is a source of uncertainty that needs to be taken into account when interpreting the displacement and bearing data.

To determine the spatio-temporal distribution of FAD and free school recaptures, we divided the western Indian Ocean, where the large majority of fish were recaptured, into eight statistical areas (Figure 1), which are subdivisions of the areas used by the IOTC for the Multifan-CL stock assessment model. Monthly recaptures at FADs and in free schools were then calculated for each statistical area.

Circular statistics

To determine whether there are any indications that FADs might influence the migratory direction of tuna, we determined the circular distribution of the bearings for each species by school type at recapture and by tagging area (Tanzanian coast, Seychelles & Mozambique Channel). We calculated mean direction in degrees and determined uniformity of movement for each group using Rao's spacing test (Rao & SenGupta 2001). This test has been noted to be the most suitable for detecting departures from uniform distributions in multimodal data than other similar tests (Bergin 1991). Rao's spacing test is based on the assumption that if the underlying directional distribution of the data is uniform, observations should be evenly spaced and approximately 360/N degrees apart. If the distribution deviates significantly from this, the null hypothesis of randomness of movement can be rejected and the movement described as directional.

To determine differences between FAD associated and free swimming fish we used Watson’s test of homogeneity between two samples (Rao & SenGupta 2001) for each species and tagging area. Watson’s two-sample test evaluates the null hypothesis that the two samples of directional data belong to the same parent population by comparing the two-sample distribution with regards to mean direction and angular variance.

In addition to comparing the two school types, we also calculated seasonal variation in migratory direction. The analysis of the spatio-temporal distribution of recaptures in areas 2a and 3a showed strong and consistent seasonal peaks of FAD recaptures and we assumed that these peaks in FAD recaptures are the result of seasonal peaks in FAD fishing effort. This allowed us to test whether fish tagged in a given area during times of assumed high FAD density showed a different migratory behaviour to those tagged at other times of the year. Since knowledge of the school type at recapture was not required for this analysis, we used the full dataset of 25,730 records.

Results

Distribution of recaptures

As table 1 shows, recaptures in FAD sets greatly exceed free school recaptures, especially for bigeye tuna. The highest density of FAD recaptures occurred in a roughly 10 degree wide strip along the east coast of Africa and in the Mozambique Channel (Figure 2). This strongly corresponds to areas of high densities of floating objects mapped by Fauvel et al. (2009) using observer data. Densities of free school recaptures on the other hand were highest in a belt between approximately 5 and 10 degrees south stretching to approximately 75 degrees east and in the Mozambique Channel, an area of relatively low FAD density (Fauvel et al. 2009).

The areas of greatest overlap between the two school types were in the vicinity of the Seychelles and in the Mozambique Channel, northwest of Madagascar (Figure 2). Examination of monthly recaptures within statistical areas showed that only the areas along the African coast (2a, 2d, 3a, see Figure 1) contained sufficient monthly recaptures for the identification of seasonal patterns. Area 2a showed a very strong and consistent pattern of peaks in FAD recaptures of skipjack and yellowfin tuna between June and December, corresponding to the seasonality of the FAD fishery in that region. Free school recaptures were consistently low for all species and showed no obvious seasonal pattern (Figure 3). Area 2d, the area with the greatest spatial overlap in FAD and free school recaptures showed strong peaks for both FAD and free school recaptures. However these did not seem to constitute a seasonal pattern (Figure 4). Figure 4 also shows that the overlap between FAD and free school recaptures in area 2d was not only spatial but also temporal. This is also true for area 3a, where both FAD and free school recaptures peak between March and June (Figure 5), corresponding to the fishing season.

Movement characteristics

As figure 6 shows, apart from a more pronounced tail at the right end of the frequency distribution for free school caught bigeye and skipjack tuna, there are no obvious differences in the frequency distribution of displacement between FAD and free school caught fish for any of the three species. The mean displacement is higher for skipjack and yellowfin tuna caught at FADs than for those caught in free schools, whereas the opposite is true for bigeye tuna. However, differences are relatively small compared to the large standard deviations (Table 2). Both mean and median displacement rates in Nm per day at liberty were higher for FAD than for free school caught fish for all species, with differences being greatest for yellowfin tuna, however standard deviations are larger than the mean in all cases (Table 3).

Rao's spacing test was highly significant ($p<0.001$) for all species, school types and tagging areas, indicating directionality of movement in all species, except for bigeye tuna tagged in the Seychelles and the Mozambique Channel. Here sample numbers were too low to reject the random direction hypothesis (Table 4). Where there was an adequate sample size, Watson's two sample test showed highly significant ($p<0.001$) differences in the underlying directional distributions between FAD and free school recaptures for all species and tagging area groupings except for yellowfin tuna tagged in the Mozambique Channel ($0.05<p<0.1$). FAD recaptured tuna tagged off the coast of Tanzania tended to have a slightly more northerly mean bearing than those recaptured in free schools, regardless of species (Figure 7). Due to their island tagging location, fish tagged in the Seychelles showed an overall greater diversity of directional movement (Figure 8) than those tagged in coastal areas. Mean direction was highly different between the two school types with FAD recaptured fish again having a stronger northerly bearing than those recaptured in free schools (Table 4). All fish tagged in the Mozambique Channel showed a strong northerly movement up of the channel with no large differences between mean migratory direction of FAD and free school recaptured fish (Figure 9).

Comparing migratory direction between fish tagged during and outside of the FAD fishing seasons in areas 2a and 3a, shows that in area 2a, all groups show directionality of movement and differences in the distributions of migratory direction between the fishing season and the rest of the year. Despite this, mean migratory directions were very similar (north-westerly) across species and seasons. Hence, assumed high FAD densities during the tagging operation did not seem to cause differences in migratory behaviour. In area 3a, seasonal differences in migratory direction could not be assessed due to small sample sizes for fish tagged during the free school fishing peak (Table 5)

Discussion

Our results show that a spatial as well as a temporal overlap between FAD and free school recaptures can occur in the Indian Ocean purse seine fishery. This can be interpreted in two ways:

Either, there is an ecological trap effect but not all individuals are affected by it or all fish were attracted to the area by the network of FADs, but their natural behaviour when trapped within a network of FADs is to alternate between associated and non associated phases (see Dagorn et al. 2007, Schaefer & Fuller 2010).

Or, there is no ecological trap effect and fish movement is determined by environmental cues or natural migratory pathways and the school type at recapture is merely a snapshot of an individual's momentary behavioural mode rather than its movement history. The latter interpretation is supported by the fact that fish tagged in the areas of spatial and temporal overlap of FAD and free school recaptures displayed the same movement characteristics regardless of whether they were tagged during periods of assumed low or high FAD densities, as one might assume that fish tagged and released during periods of high FAD densities would have a higher probability of being trapped by a network of FADs and therefore displaying different movement behaviour.

As regards tuna movement characteristics, we found no large differences in mean displacement and mean displacement rate between FAD and free school caught fish for any of the three species. While differences in median displacement rates between FAD and free school recaptures for yellowfin and skipjack tuna follow the same pattern of higher medians for FAD caught fish described by Hallier and Gaertner (2008) in the Atlantic, the differences are much smaller. The distribution of times at liberty for the Atlantic data used by Hallier & Gaertner is unknown, however, mean time at liberty for the Indian Ocean data was relatively high at 243 days (sd=195 days). This makes the straight-line estimation of displacement and displacement rates highly imprecise, as fish are more likely to stray from straight-line trajectories the longer they are at liberty. It is therefore questionable whether displacement rate is a suitable movement parameter for the determination of a FAD effect on tuna migratory behaviour in the Indian Ocean. This issue could be further investigated by statistical analysis of the displacement distributions.

While our findings on movement direction of FAD and free school captured fish mirror those of Hallier & Gaertner (2008) we do not necessarily share their suggestion that this might indicate an impact of FADs on the migratory movement of tropical tuna. Fauvel et al. (2009) showed that in the case of the Indian Ocean, FADs are not randomly distributed. Mean movement directions of FAD recaptured fish from the three main tagging areas roughly correspond to the angle from the tagging location to the highest concentration of FADs off the Somali coastal region. As fish recaptures are entirely fishery dependent, this could suggest that movement angles are artefacts of the distribution of FAD fishing effort rather than the result of a FAD effect on migratory movement. Moreover, the uncertainty in the final recapture location means statistical testing of net displacements may be ill suited to detecting complex movement patterns and the possible influence of FADs. Therefore, at this stage, it is not possible to conclude whether fish caught at a FAD display different movement characteristics because they were attracted to their recapture location by a trap effect of the FADs, or were simply caught at FADs because they encountered them while following natural migratory pathways whereas those travelling in a different direction simply did not encounter any FADs and were therefore caught in free schools.

To address the question of FAD effects on movement behaviour more definitively, we suggest estimation of movement models from the mark recapture data. Relevant modelling approaches for future work may include advection – diffusion – reaction models (Kleiber & Hampton 1994; Sibert et al 1999) or spatial Brownie-Peterson models (Eveson et al. 2009). In either case the influence of FAD density, either from observer or FAD tracking data, on movement probabilities could be estimated, regardless of school type at recapture. Moreover, data from archival or pop-up data would considerably help to assess whether FADs play a role in detemining of large-scale tuna movements. The MADE project has already made some progress in this matter by deploying archival tags on a few bigeye and yellowfin tuna, but unfortunately the number of tags deployed to date is very low, as the threat of piracy has hindered field operations in large parts of the Western Indian Ocean.

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Figures

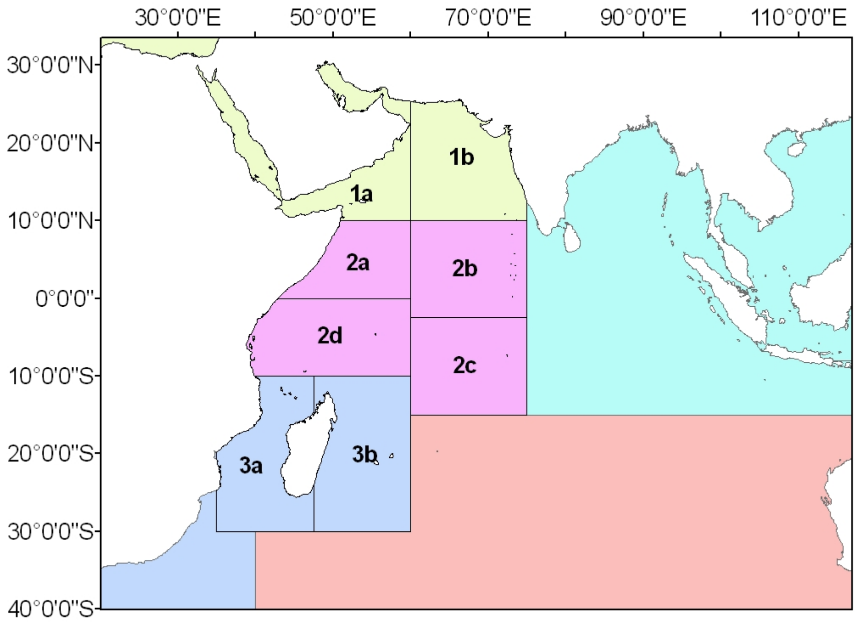

Figure 1. Statistical areas for mark recapture data analysis. Colours indicate areas used for the IOTC Multifan-CL stock assessment model. Labels indicate subareas used for this study.

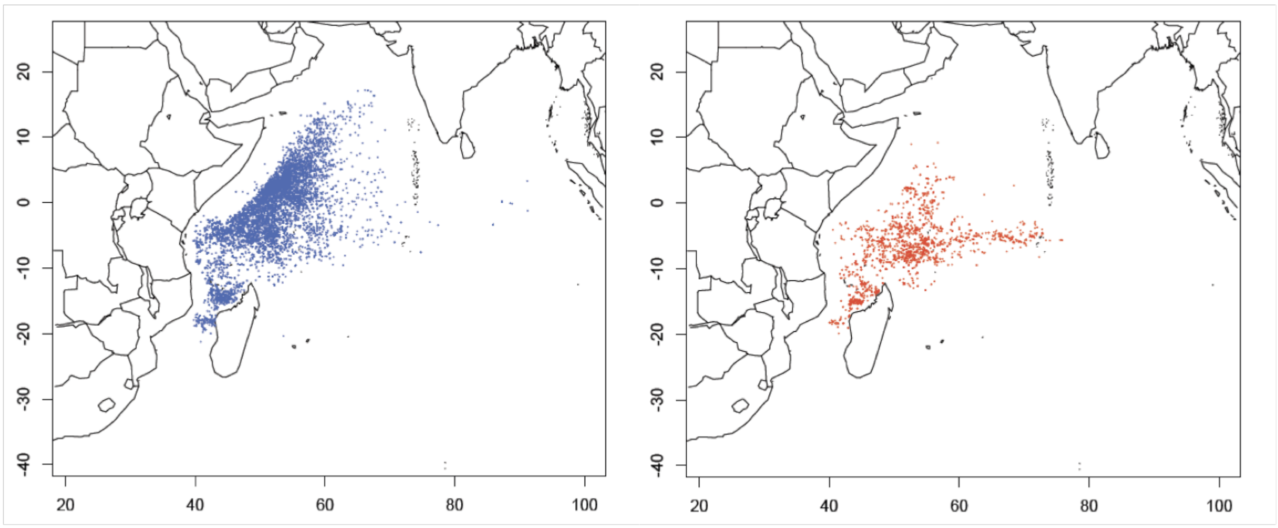

Figure 2. Recapture locations for all three species by school type at recapture. Blue dots indicate FAD school recapture locations, red dots indicate free school recapture locations.

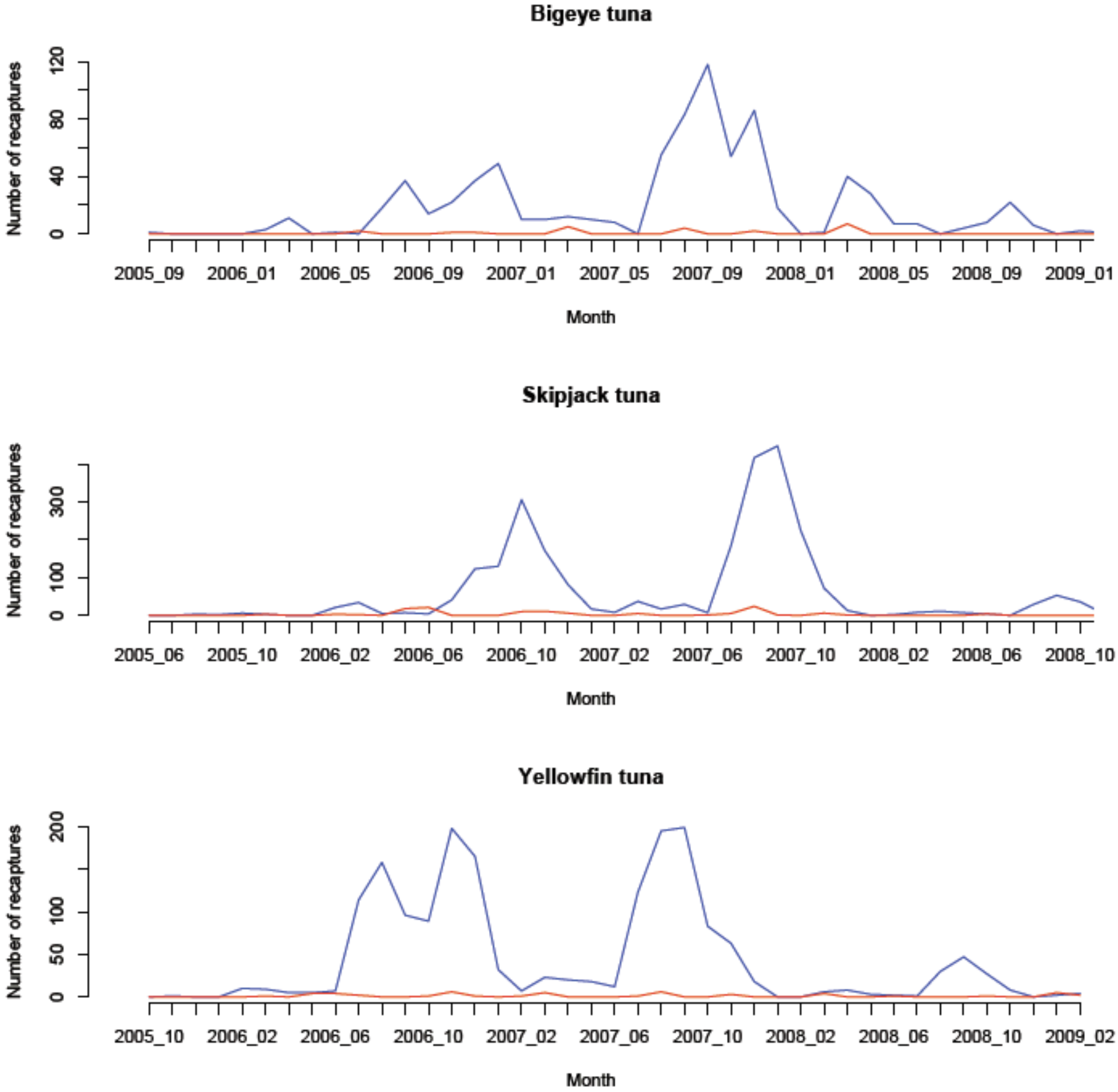

Figure 3. Monthly number of recaptures in statistical area 2a by school type at recapture for the three tuna species. Blue lines indicate FAD school recaptures, red lines indicate free school recaptures.

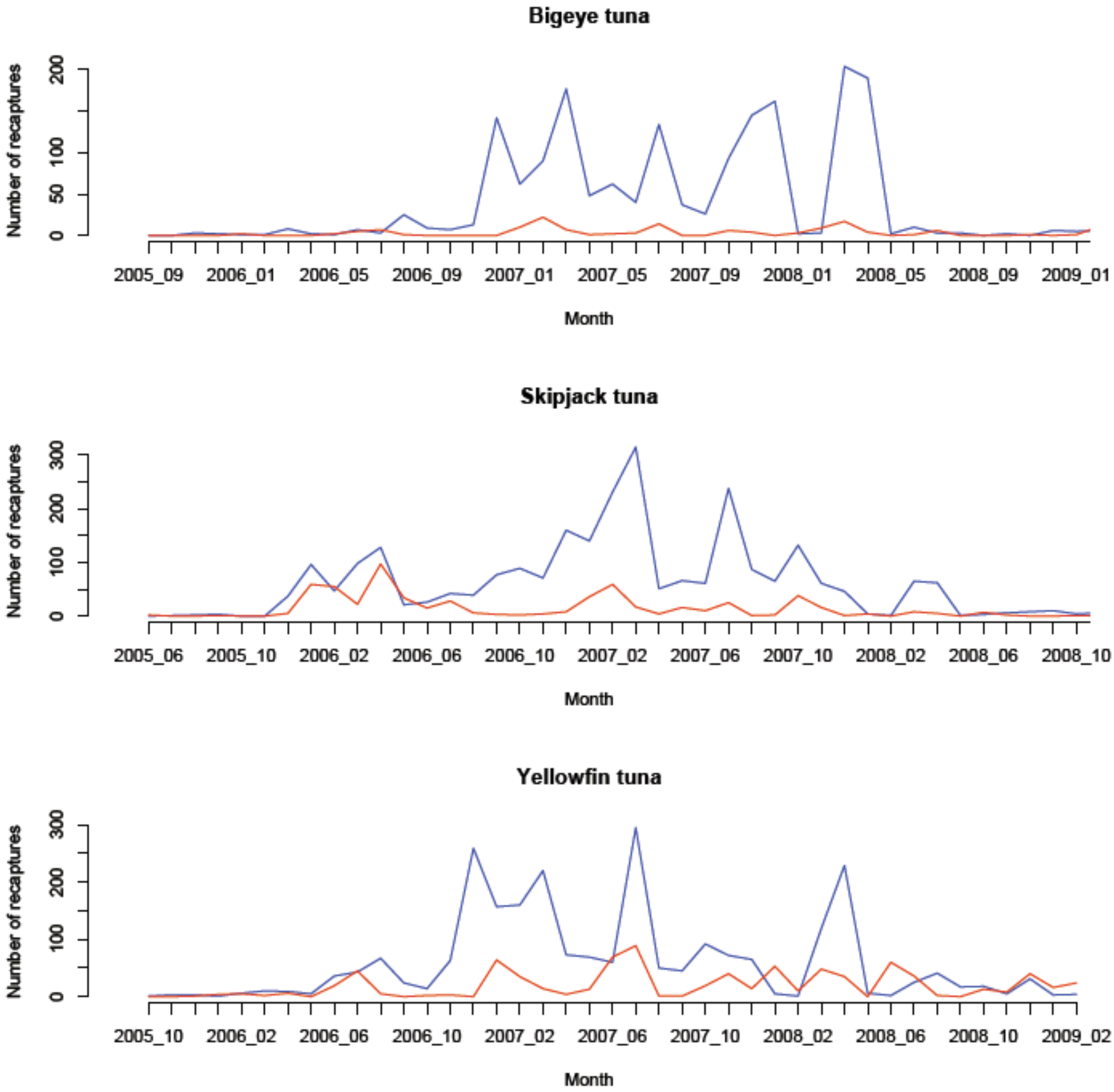

Figure 4. Monthly number of recaptures in statistical area 2d by school type at recapture for the three tuna species. Blue lines indicate FAD school recaptures, red lines indicate free school recaptures.

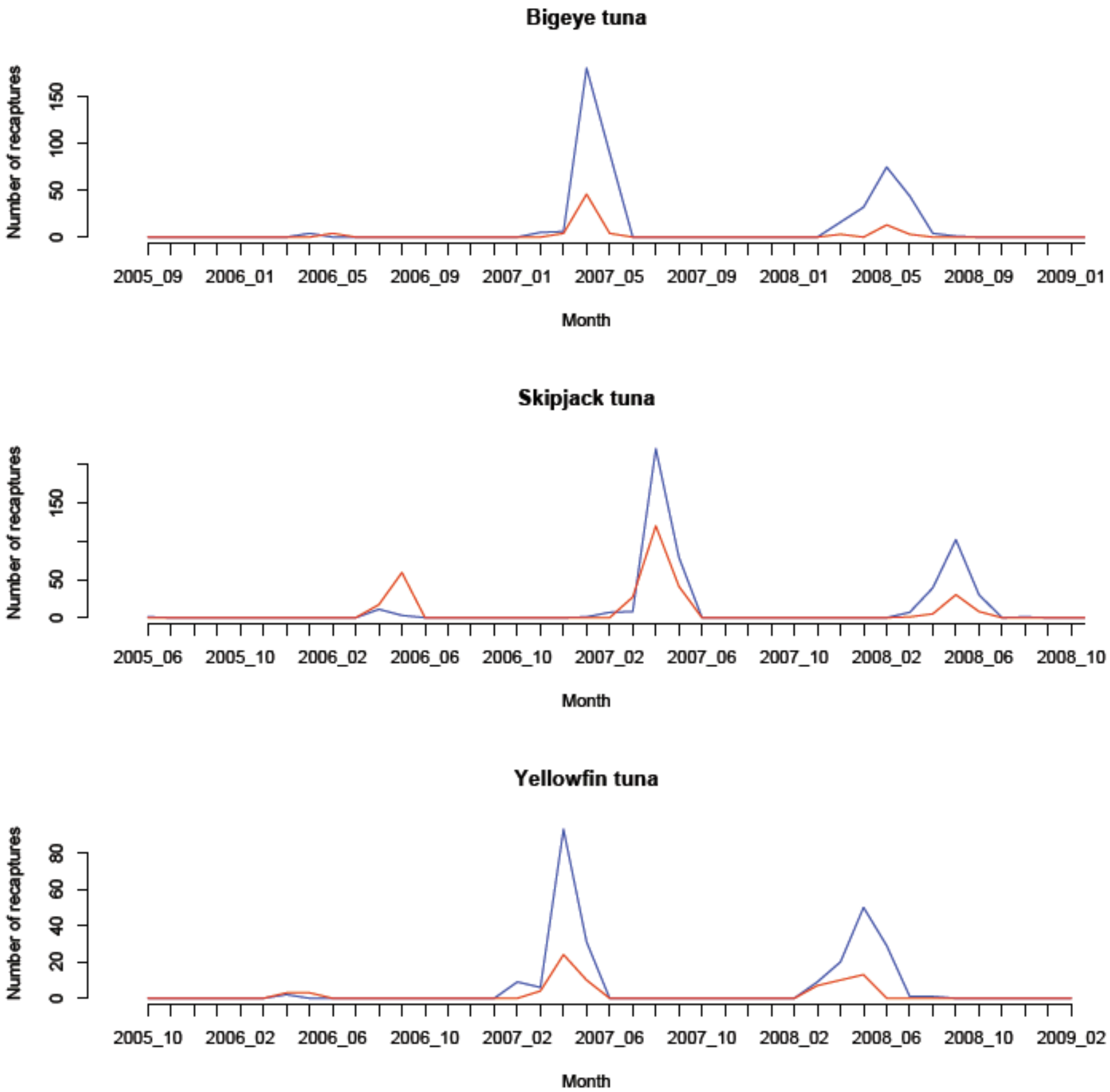

Figure 5. Monthly number of recaptures in statistical area 3a by school type at recapture for the three tuna species. Blue lines indicate FAD school recaptures, red lines indicate free school recaptures.

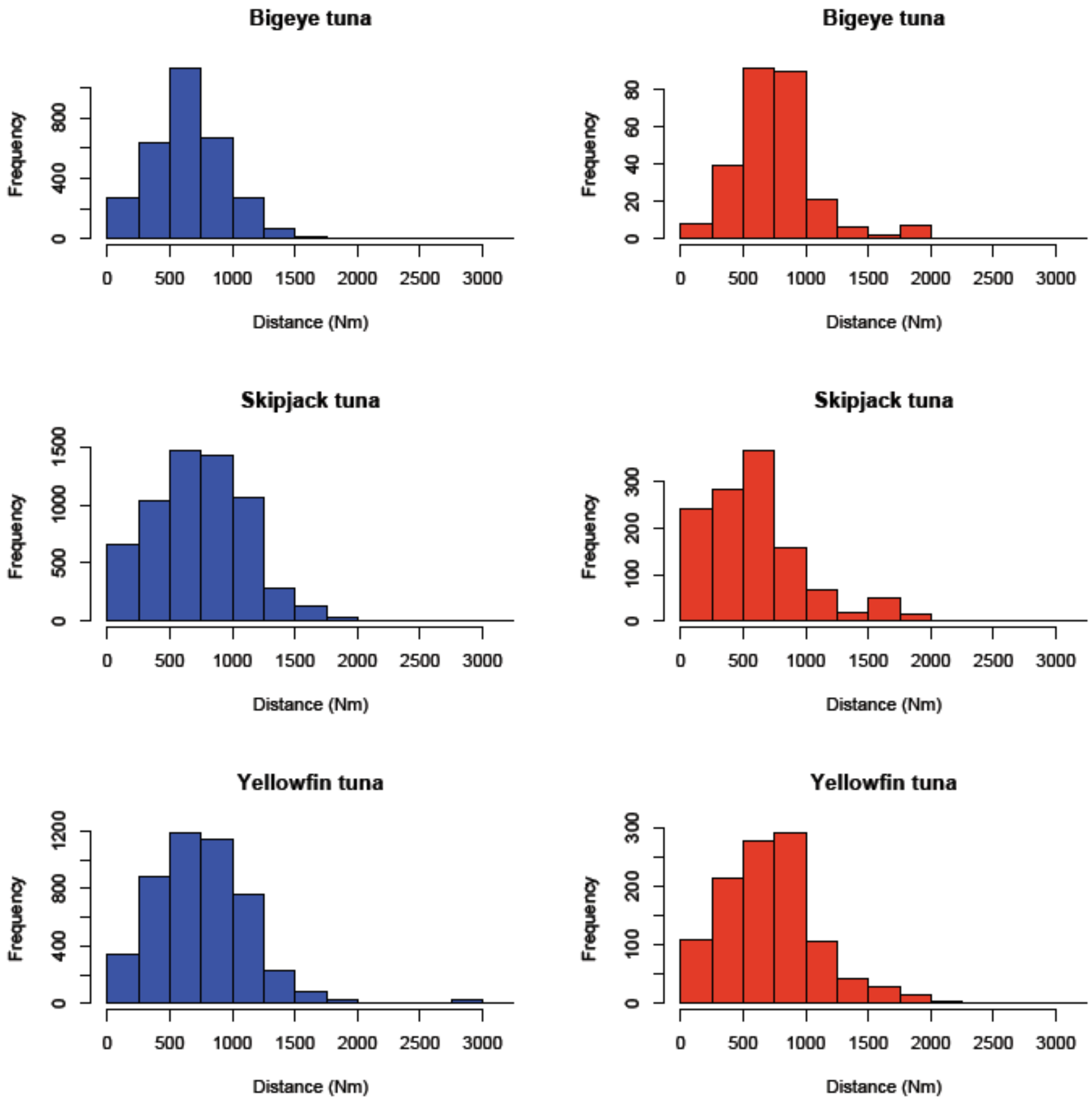

Figure 6. Frequency distribution of displacement in nautical miles by school type at recapture for the three tuna species. Blue bars indicate FAD school recaptures, red bars indicate free school recaptures.

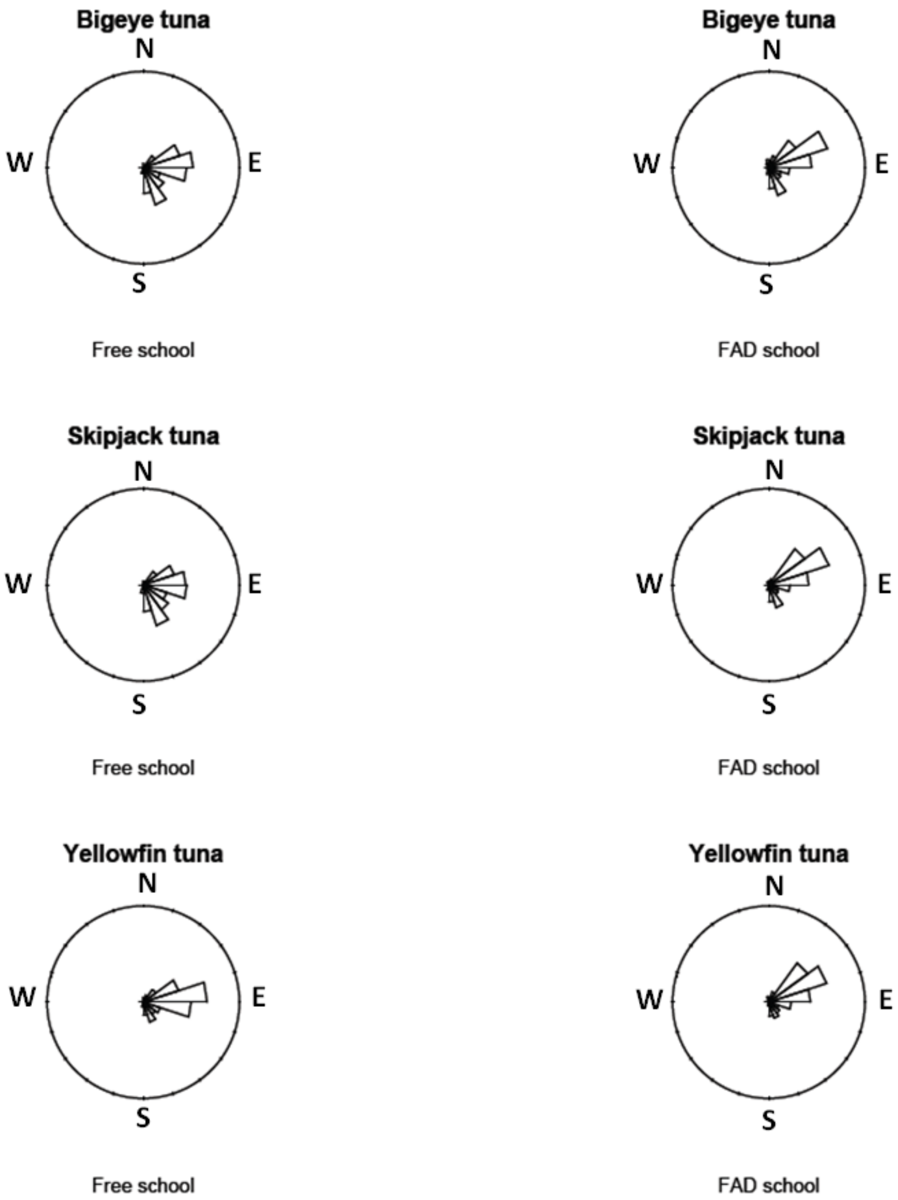

Figure 7. Movement angle distribution for the three tuna species tagged off the Tanzanian coast by school type at recapture.

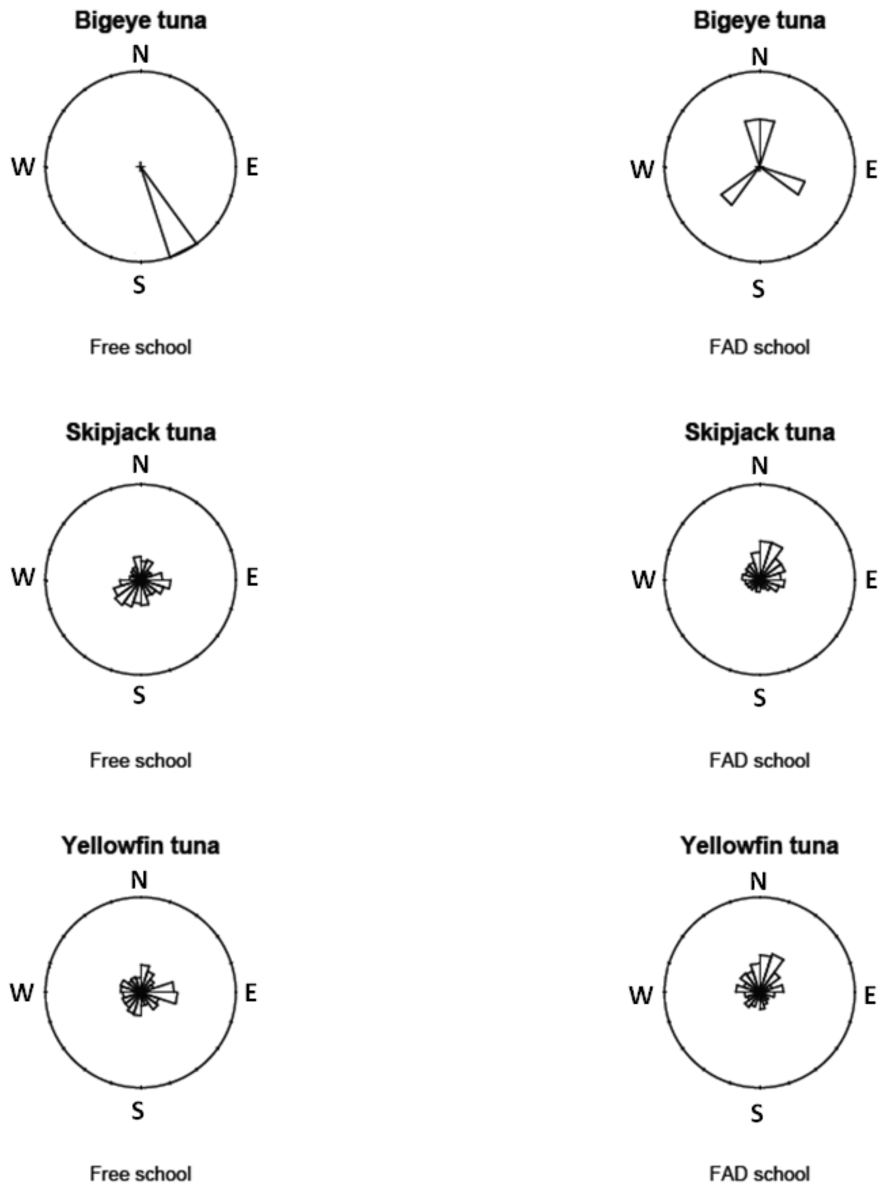

Figure 8. Movement angle distribution for the three tuna species tagged around the Seychelles by school type at recapture.

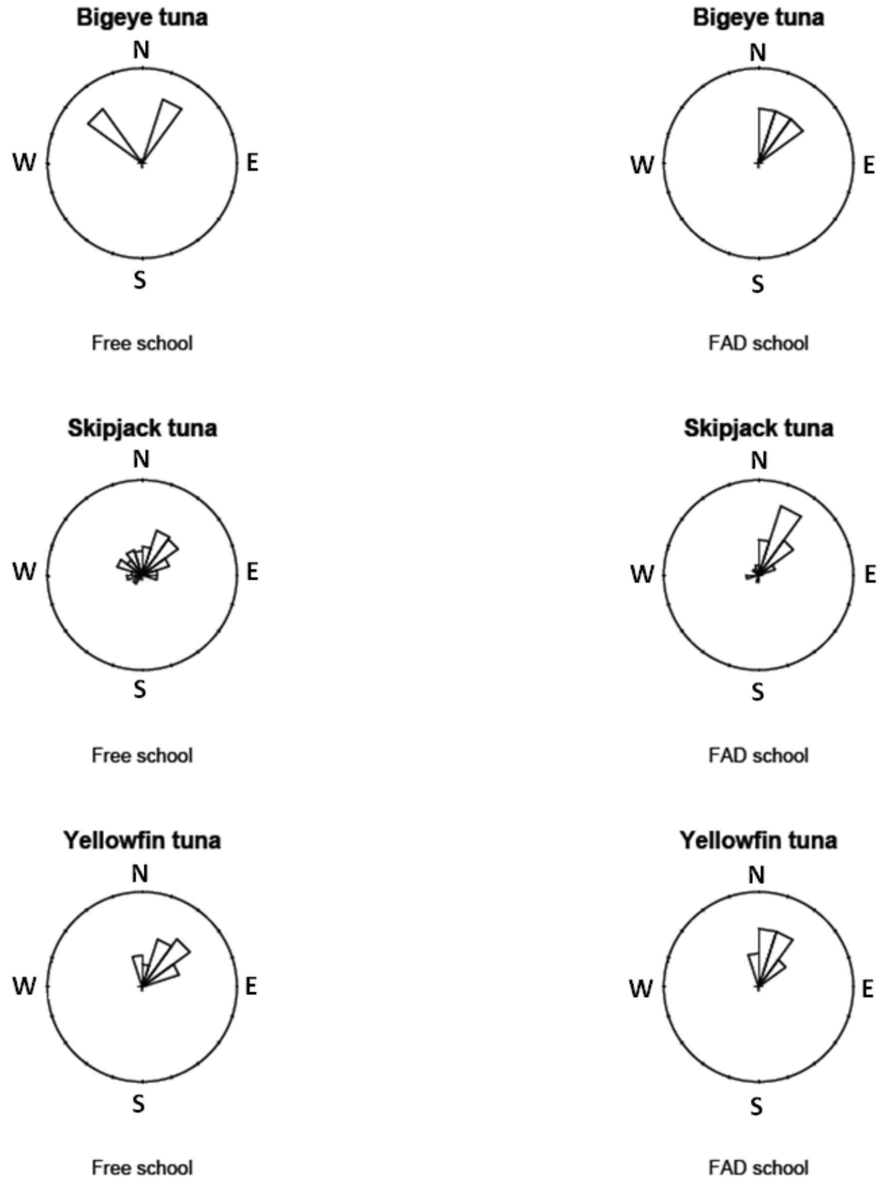

Figure 9. Movement angle distribution for the three tuna species tagged in the Mozambique Channel by school type at recapture.

Tables

Table 1. Number of recaptures in FAD associated and free schools for the three tuna species from the IOTC mark-recapture database

	FAD	Free school
Bigeye tuna	3069	264
Skipjack tuna	6110	1195
Yellowfin tuna	4681	1084

Table 2. Mean displacement and standard deviation (SD) in nautical miles by species and school type at recapture

		Mean	**SD**
Bigeye tuna			
	FAD	652.81	303.01
	Free	756.50	311.26
Skipjack tuna			
	FAD	741.96	382.02
	Free	587.09	385.75
Yellowfin tuna			
	FAD	759.03	381.06
	Free	716.74	373.82

Table 3. Mean, median and standard deviation (SD) of displacement rate in nautical miles per day by species and school type at recapture

		Mean	Median	SD
Bigeye tuna				
	FAD	5.88	3.05	13.66
	Free	4.04	2.43	6.16
Skipjack tuna				
	FAD	6.74	3.60	9.63
	Free	5.75	2.80	21.09
Yellowfin tuna				
	FAD	7.13	3.55	17.01
	Free	2.47	1.48	3.59

Table 4. Sample size (n), mean direction, Rao's spacing test of uniformity (Rao's U) and Watson's two sample test of homogeneity (Watson's U^2) for the three tagging areas and three tuna species by school type at recapture. Significance levels are <0.001 unless stated otherwise. *p>0.1, **0.05<p<0.1

		n	Mean direction	Rao's U	Watson's U^2
Tanzanian coast					
Bigeye					
	FAD	3062	78.0	252.48	4.06
	Free	261	103.7	249.52	
Skipjack					
	FAD	4682	71.8	268.92	18.32
	Free	674	111.4	243.53	
Yellowfin					
	FAD	4482	68.3	268.85	21.09
	Free	865	88.5	268.13	
Seychelles					
Bigeye					
	FAD	4	23.1	82.93*	-
	Free	1	146.6	-	
Skipjack					
	FAD	1211	28.0	183.63	8.03
	Free	441	177.5	155.95	
Yellowfin					
	FAD	160	4.8	167.02	1.36
	Free	200	90.6	161.63	
Mozambique Channel					
Bigeye					
	FAD	3	27.0	-	-
	Free	2	356.5	-	
Skipjack					
	FAD	180	28.5	298.33	1.03
	Free	78	17.5	195.29	
Yellowfin					
	FAD	8	16.4	267.58	0.16**
	Free	18	34.2	251.75	

Table 5. Sample size (n), mean direction, Rao's spacing test of uniformity (Rao's U) and Watson's two sample test of homogeneity (Watson's U^2) for the two tagging areas that displayed seasonal patterns in recaptures and the three tuna species by fishing season. Significance levels are <0.001 unless stated otherwise. *p>0.1, **0.05<p<0.1

	N	Mean direction	Rao's U	Watson's U^2
Tanzanian coast				
Bigeye				
01 - 06	1263	70.34	236.64	4.39
07 - 12	2109	63.61	272.53	
Skipjack				
01 - 06	1493	64.26	272.81	2.23
07 - 12	4374	62.15	291.42	
Yellowfin				
01 - 06	2705	64.75	255.76	3.27
07 - 12	4446	61.01	272.89	
Mozambique Channel				
Bigeye				
07- 03	0	-	-	-
03- 06	9	30.96	182.74**	
Skipjack				
07- 03	3	24.61	-	0.12*
03- 06	460	23.93	246.81	
Yellowfin				
07- 03	2	33.61	-	0.12*
03- 06	89	92.08	261.80	