

EFFECTS OF FISH AGGREGATING DEVICES (FADS) ON TUNA
MOVEMENT

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ABSTRACT

Tuna are often found in association with floating objects and remain near them. Taking advantage of this behavior, man-made floating objects, referred to as fish aggregating devices (FADs) are commonly used in tuna purse seine fisheries. As much as half of the worlds tuna catch now comes from schools associated with FADs as their use continues to rise. Despite the prevalence of FAD, little is known about FADs effects on tuna movement. In this dissertation, I modified the Advection-Diffusion Reaction (ADR) model with the inclusion of FAD effects by modeling the attraction and hindering tendencies of FAD to tuna. In my ADR-FAD model, the advection and diffusion are modulated by FAD distribution. To verify the ADR-FAD model, more than 10,000 simulations were conducted using conventional tag release-recapture data, fishing effort data and FAD sets data as a proxy for FAD distribution. Skipjack tag data from the Pacific Tuna Tagging Programme was analyzed using the ADR-FAD model and the original ADR model. Both models show similar results but the ADR-FAD model fits significantly better than the ADR model. Differences in the effects of FAD between the open and coastal ocean were found, suggesting FAD use should be managed and regulated differently between the coastal and open ocean. I also applied the ADR-FAD model to two different skipjack tag datasets from the Regional Tuna Tagging Programme (1989-1992) and the Pacific Tuna Tagging Programme (2006-present) to compare the effects of FAD over the two periods. The density of FAD increased three folds since the 1990's, and the spatial distribution differs between the two periods. FAD induced skipjack movement is significantly higher in the 2000's, while diffusive movement in the 2000's is reduced when compared to the 1990's. Even though tuna movement is tied to environmental and trophic conditions, model results indicate rapid expansion in FAD use exerts considerable influences on tuna movement.

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CHAPTER 1

INTRODUCTION

1.1 History on fishing around floating objects

This dissertation concerns the influence of Fish Aggregating Devices (FADs) on tuna. Since the massive use of FADs in tuna fisheries, the effects of FADs has been discussed by many fisheries scientists but they still remain questionable. Tuna and many other pelagic fish associate with objects floating on the ocean surface, such as logs and branches, in the open ocean. The earliest record using man-made floating objects date back to 200 AD by the Roman author Oppian (cited in *Dempster and Taquet (2004)*). He described floating objects used to catch dolphinfish (*Coryphaena hippurus*) in the Mediterranean. In different parts of ocean, Japanese fishers used anchored ‘tsukegi’ raft developed in 1650 (*Nakamae 1991*). In beginning of 20th century, traditional bamboo rafts anchored near to the coast to attract pelagic fish in Indonesia, Malaysia and the Philippines with different names of ‘rumpon’, ‘unjang’ and ‘payao’ respectively (*Anderson and Gates 1996*). In the late 1950’s, the tuna purse seiners in the eastern Pacific Ocean found that catching tuna schools associated with natural floating objects was possible (*Hall 1998*). The thermocline in the eastern Pacific Ocean is shallow, so it allowed small purse seines nets to reach the fish schools. However, the thermocline in the western Pacific Ocean is much deeper than in the eastern Pacific and similar fishing operations system did not work to catch tuna schools. Japanese purse seiners using a deeper and fast sinking nets started fishing on floating object in the 1960s (*Miyake et al. 2010*). The fishing system has been adopted by other commercial tuna purse seiners in the Western and Central Pacific Ocean (WCPO) since the early 1980’s. Thereafter, commercial tuna purse seiners focused on using floating objects in open oceans.

1.2 Hypotheses on aggregating behavior

Previous investigators have framed different hypotheses to explain why pelagic fish aggregate around floating objects. The first hypothesis was mentioned by *Suyehiro* (1951) that tuna schools used floating object as a shelter from predators. He stated fish tend to associate with floating objects or bigger creatures such as whale shark perceiving the danger in the open ocean. However, the hypothesis does not apply to tuna schools because often enormous tuna schools are found under a small floating object which cannot be a shelter for them.

The second hypothesis is floating objects may be an indicator of food. *Bard et al.* (1985) suggests that a floating object aggregates small fish in its close vicinity on which large fish could prey. However, no evidence was found that the amount of small fish near floating object is sufficient for tuna to prey. Similar hypothesis is that floating objects are often indicators of productive areas, either because the natural debris (e.g. logs) originate in areas with additional terrigenous inputs and remain within these rich bodies of water (i.e. river mouth), or because they aggregate in rich frontal convergence zone (*Hall* 1992). The hypothesis that tuna can detect floating objects more easily than prey is sufficient to support the hypothesis, but it has not been demonstrated yet.

The third hypothesis is floating objects may provide spatial references in unstructured open ocean (*Klima and Wickham* 1971). Yellowfin tuna have a tendency to return to the FAD where they were tagged with temporal regularity (*Klimley and Holloway* 1999). However, many conflict cases that tagged tuna didn't return to the FAD were found in other studies (*Holland* 1990).

The last hypothesis is floating objects may be used as meeting points for tuna where they can increase the encounter rate between isolated individuals or small schools and other schools (*Dagorn and Fréon* 1999; *Fréon and Dagorn* 2000). A fish joining a greater group will increase its probability of survival, until an optimal size is reached (*Pitcher and Parrish* 1993). The experimental study on the social behavior of tuna under two identical FADs found that asymmetrical distribution of tuna biomass (*Robert et al.* 2013). They concluded from the observation that social interactions which is important to explain the meeting point hypothesis underlie aggregating process.

1.3 Purse seine fishing on floating objects

There are a couple advantages using floating objects in tuna fisheries (*Dagorn et al.* 2013): First, it reduces searching time for tuna school because they are visible on the surface. When fishers find floating objects they can track them. This allows them spend less time to find tuna schools. Second, it increases the success rates of fishing. Schools around floating objects (associated schools) are usually less mobile than free-swimming schools (unassociated schools). Therefore associated schools showed higher success rates (90%) than sets on free-swimming schools (50%) (*Suzuki et al.* 1999; *Fonteneau et al.* 2000; *Miyake et al.* 2010). These advantages lead fishers started to build and use artificial fish aggregating devices (FADs, i.e. man-made floating objects) rapidly. The development of FAD was started with attaching reflectors to the logs, and later, radio buoys, GPS, and transmitter. The effort allowed fishers to find their FADs in real time from long distances. Recently, echosounders are used for FADs to inform fishers the existence of fish and these can estimate the amount of the fish biomass under the FADs. The efficiency of FAD increased the catchability of tuna. Nearly half of the world tuna catch (by weight) is made from associated schools. Tuna catches by associated schools reached one million tons since 1998. In the Western and Eastern Pacific Ocean, catches on floating objects account for about 50% of the overall catch of tuna in these oceans (Figure 1.1a, from *Dagorn et al.* (2013)). Since 1990, the proportion of catch on floating objects increased suddenly in the Western and Central Pacific Ocean. This is due to the dramatic expansion of FADs use in this region (Figure 1.1b from *Dagorn et al.* (2013)). This expansion is important because the catch in the Western and Central Pacific Oceans accounts for over 50% of the world tuna production.

Three types of floating objects are used in tuna fisheries: natural log (log), anchored FADs (aFADs) and drifting FADs (dFADs). ‘Log’ refers to any natural object and ‘FAD’ refers to any man-made floating object built for the purpose of fisheries. FAD can separate two types; aFADs are moored in fixed location and used in small-scale coastal and semi-artisanal fisheries, whereas dFADs are freely in the ocean currents and used by industrial purse seine fisheries in open ocean.

1.4 Impacts of floating objects

The massive use of FADs raises the possibility of three negative impacts: 1) high levels of by-catch of non-tuna species (*Amandè et al.* 2010; *Chassot et al.* 2009; *Romanov* 2008; *Dempster and Taquet* 2004; *Castro et al.* 2002; *Druce and Kingsford* 1995); 2) high catch of juvenile yellowfin and bigeye tuna (*Miyake et al.* 2010; *Williams and Terawasi* 2011); and 3) disruption of natural movement of tuna (*Hallier et al.* 2008; *Bromhead et al.* 2003; *Marsac et al.* 2000; *Fonteneau et al.* 2000). First concern is the disturbance on pelagic ecosystem by increase by-catch. The diverse species are found under floating objects. It is an order of magnitude greater than species diversity in open water (*Druce and Kingsford* 1995). *Castro et al.* (2002) found 333 species of fish belonging to 96 families associated school with floating objects by review of other studies. These species are taken when purse seiners fish on FADs (*Hall* 1998; *Romanov* 2008; *Amandè et al.* 2010). Removing concerned amount of non target species or removing certain species can disturb pelagic ecosystem. Second concern is the catch on small tuna can cause the reduction in tuna population. Associated school around floating objects has much higher proportion of juvenile yellowfin and bigeye tuna compared to non-associated school. Domestic fisheries in the Philippines and Indonesia is mostly conducted on anchored FADs in coastal areas, and takes large number of small yellowfin and bigeye tunas (*Miyake et al.* 2010)(*Williams and Terawasi*, 2010). The catch of juvenile bigeye tuna has increased considerably since 1996 when the drifting FADs were introduced in purse seine fishery (*Williams and Terawasi*, 2010). Capturing large proportion of juvenile fish decreases the yield per recruit, thus, these catches of juveniles are a threat to the viability of the tuna populations. Because the stock size of bigeye tuna is much smaller than the stock size of yellowfin tuna, the impact of the catch of juvenile bigeye tuna is much more serious than it is on the yellowfin tuna (*Aires-da-Silva and Maunder*, 2009, *IATTC* 2008). Not surprisingly, the stock of bigeye tuna in the Pacific has shown signs of over exploitation, with declining biomass. The bigeye tuna stock assessment (*Harley et al.*, 2010) shows that both total biomass and spawning biomass have declined to the half of their levels in 1970. It concluded that overfishing is occurring in the bigeye tuna stock in the Western and Central Pacific Ocean. The depletion of yellowfin tuna stock in same area also suggests purse seine fishing on floating object as a main reason (*Langley et al.* 2009). The last concern on using FADs

in the purse seine fishery is the disturbance on tuna's movements by FADs, in particular drifting FADs. The large number of FADs are continuously deployed in the oceans. In the eastern Pacific Ocean (EPO), the estimated FADs deployment was more than 7000. That number indicates that a vessel deploys 50-75 FADs annually (WCPFC, 2009). The actual number of FAD deployments is not available in the western and central Pacific Ocean (WCPO). However, the number of FAD sets was increased from 6652 in 2006 to 11778 in 2008 (WCPFC, 2009). Several studies speculate that the numbers of FADs might function as 'ecological traps' (*Fonteneau et al.* 2000; *Hallier et al.* 2008). The hypothesis of ecological trap is a situation in which population growth is reduced as a consequence of individuals making a maladaptive habitat choice (Gates and Gysel 1978, Schlaepfer et al., 2002). FADs may work as ecological traps for tuna because: (1) the large number of FADs can alter the natural movements of tuna, (2) the aggregation of small tuna under FADs is a fast, strong and long-lasting process, and (3) consequently, FADs affect growth and natural (and fishing) mortality of small tuna (*Marsac et al.* 2000). *Hallier et al.* (2008) found fish from associated schools are less healthy than those from unassociated schools. This result substantiates that the attraction and the retention of tuna around FADs affects them negatively in their growth and condition. Fishing on natural floating objects occurred before the use of FADs. Then the fishing on FADs may think that it is an expansion of the fishing on natural floating objects. However, the impact of natural floating objects and the impact of FADs on tuna are different because of their different oceanic distributions. Natural logs are washed down from large rivers flowing through equatorial forests and mostly drift towards biologically productive areas while FADs are generally deployed offshore where the ecosystem is generally has less productive than coastal areas (*Marsac et al.* 2000). Therefore, the attraction and the retentions of tuna around FADs may drive them in non-productive areas.

To find out whether FADs are working as ecological traps for tuna, the question should start from whether deploying FADs takes tuna to places where they normally not go. It is difficult to answer the question because tuna's 'normal' movement patterns are still unknown. The movements of tuna have been studied with tuna tagging data using the Advection-Diffusion Reaction Model

(ADRM) for decades *Sibert et al.* (1999). The ADRM is an good analysis method to analyze tuna tagging data because it analyzes the spatial and temporal change in population density including the concept of random movement. In this model, movement is partitioned into directed and dispersive components. The directed component (advection) refers to net displacement in a unique direction, and the dispersive component (diffusion) is the random movement. The model has been used to analyze tuna tagging data for decades in the Western and Central Pacific Ocean (WCPO). If the movement of tuna before using FADs considers as the normal movement of them, I may answer the question that the numbers of FADs altered the movement of tuna by comparing the movements from two. My approach is using the ADR-FAD model which has FAD as a forcing to control the movement of fish. The main idea of the model is that when an area has more FADs than other areas, the movements of fish depend on the number of FADs.

1.5 Research Objectives and Structures

The goals of this dissertation are: 1) to develop and test the ADR-FAD model with real data, 2) to determine the impact of FADs on movement of tuna by applying the model with tags from two different time periods (1990's and 2000's).

1.5.1 Chapter 2

Chapter2 describes the ADR-FAD model and verifies it by simulation tests. The ADR-FAD model is designed based on the attraction and hindering tendency of FADs to tuna. The advection and diffusion component in the model are controlled by FADs by following hypothesis: 1) the directional movement of tuna is forced by the gradient of FAD density, and 2) the diffusive movement of tuna is reduced with higher FAD density.. ADR-FAD model simulations were conducted using real tag data, fishing effort data, and FAD sets data. More than 10,000 simulations were computed to find the better remedies under the data limitation.

1.5.2 Chapter 3

In chapter 3, I compared the results of the ADR model and ADR-FAD model using the skipjack conventional tag data from the most recent tagging program to verify the FAD effects on the movement of skipjack population. I also applied the ADR-FAD model in the two-regional domains: coastal and open ocean. Any regional differences in the effects of FADs may imply the difference of anchored FADs and drifting FADs since anchored FADs are dominant in the coastal ocean and drifting FADs are common in the open ocean.

1.5.3 Chapter 4

In chapter 4, the ADR-FAD model was applied to skipjack tag data from the 1990's tag data and the 2000's tag data. The model results were compared to find the difference of their movement and the FAD effects on the movement of skipjack population. By comparing the result, how the massive loading of FADs in the WCPO changed their movement and how the influence of FADs on their movement changed over time.

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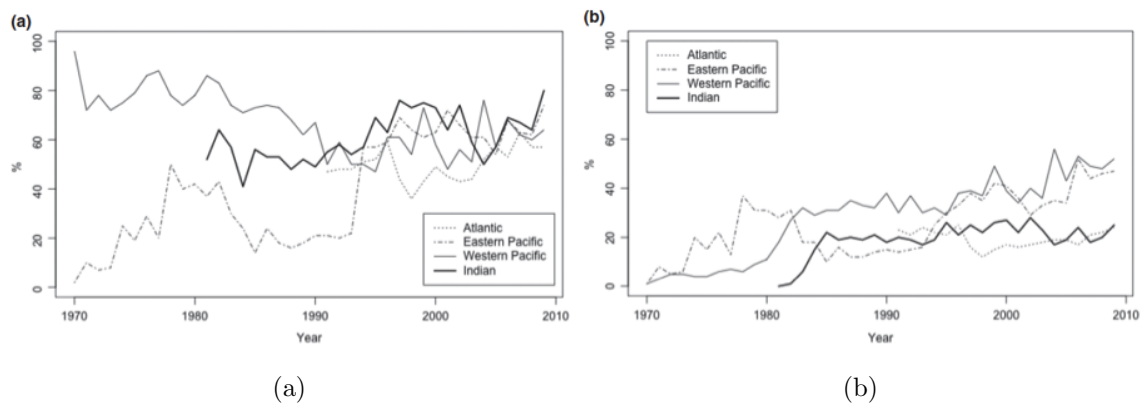


Figure 1.1: Annual trends in the percentage of the catch of bigeye, yellowfin and skipjack tunas made on floating objects by ocean regions, (a) relative to total purse seine catch. (b) relative to all fishing gears (from *Dagorn et al.* 2013).

CHAPTER 2

MODEL DESCRIPTION AND VERIFICATION

2.1 Model description

2.1.1 Advection-Diffusion Reaction Model (ADRM)

The basic model used by this work is the Advection-Diffusion Reaction Model (ADRM). The ADRM estimates movement and mortality of fish population using tagging data (*Sibert et al. 1999*). Movement is represented by an advection-diffusion process, which is the population equivalent of individual movement (*Okubo and Levin 2001*). The model parameters are as follows: 1) movement parameters are homogeneous within geographical regions; 2) fishing mortality is proportional to fishing effort; and 3) natural mortality is constant over area and time. All parameters are estimated simultaneously at maximum likelihood.

The number of tagged fish per unit area satisfies the following partial differential equation that shows the local rate of change of tag density (N) at point (x, y) :

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial N}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial N}{\partial y} \right) - \frac{\partial}{\partial x} (uN) - \frac{\partial}{\partial y} (vN) - ZN \quad (2.1)$$

On the right side of equation 4.2.2, the first two terms describe dispersive movements in terms of the ‘diffusion’ parameter D . The second two terms characterize directed movement in terms of the ‘advection’ parameters u, v that describe east-west and north-south movement, respectively. The last term describes the loss of tagged fish by fishing and natural mortality. Total mortality (Z) is defined as

$$Z_{xyt} = M + \sum_f F_{xyt} \quad (2.2)$$

where F_{xyt} is the mortality due to fishing by fishing fleet f operating at point (x, y) during time step t . The natural mortality (M) is assumed to be constant at all times and locations. Fishing mortality is assumed to be a simple function of observed fishing effort

$$F_{xyt} = q_f \cdot E_{xyt} \quad (2.3)$$

where E_{xyt} is the observed fishing effort of fleet f operating at point (x, y) during time step t . The variable q_f is the catchability coefficient, which indicates a fleet specific proportionality constant of fish catch by unit of fishing effort.

Closed boundary conditions are used in the model, which means that no fish can move out of the boundaries of the model domain. Hence, on the boundaries,

$$\begin{aligned} u &= 0, \\ v &= 0, \end{aligned} \quad (2.4)$$

and,

$$\begin{aligned} \frac{\partial N}{\partial x} &= 0, \\ \frac{\partial N}{\partial y} &= 0. \end{aligned} \quad (2.5)$$

These conditions ensure that tagged tuna numbers stay in the model domain when fishing and natural mortalities are zero. The initial condition for N is

$$N_{xy0} = \begin{cases} \sum_c \tilde{N}_{x_c y_c 0_c}, & \text{tag release sites,} \\ 0, & \text{elsewhere.} \end{cases} \quad (2.6)$$

where $\tilde{N}_{x_c y_c 0_c}$ is the number of tagged fish released at point (x_c, y_c) at time 0 in tag cohort c . A cohort here is defined as total tagged fish released in a one-degree geographic square at time t . Therefore, $\tilde{N}_{x_c y_c t_c}$ is the density of tagged tuna at point x, y in the ocean at time t in tag release cohort c . The aggregated density of tagged tuna (N) from all cohorts released up to time t is given by

$$N_{xyt} = \sum_{c=1}^{c_t} \tilde{N}_{x_c y_c t_c}. \quad (2.7)$$

2.1.2 FAD Sub-models

Tuna are attracted by Fish Aggregating Devices (FADs) and tend to stay near them (*Girard et al. 2004; Dagorn et al. 2007; Ohta and Kakuma 2005; Kleiber and Hampton 1994*). Based on the attraction and hindering tendency of FADs, the advection and diffusion components in the ADRM are controlled by FADs. Two sub-models, FAD-Advection and FAD-Diffusion sub-model, are constructed under the following hypotheses.

- 1) The directional movement (u, v) is forced by the gradient of FAD density.
- 2) The diffusive movement (D) of tuna is reduced with higher FAD density.

FAD-Advection Model

The FAD-Advection model is based on the simple rule that tuna in a region with lower FAD density tend to move toward a neighboring region with higher FAD density. The gradient of habitat was used as a part of advective movement in the spatial ecosystem and population dynamic model (SEAPODYM) (*Lehodey et al. 2008*). In this model, the FAD density gradients control the directional movement of tuna along with their ‘natural’ movement. The total advection (u, v) is the algebraic sum of the natural movement (u_r, v_r) , which are constant over the domain except at the boundaries (equation 2.4), and the movement induced by the FAD $(\psi \cdot \frac{G_x}{|G|_{max}}$ and $\psi \cdot \frac{G_y}{|G|_{max}}$):

$$\begin{aligned} u &= u_r + \psi \cdot \frac{G_x}{|G|_{max}}, \\ v &= v_r + \psi \cdot \frac{G_y}{|G|_{max}} \end{aligned} \tag{2.8}$$

when

$$\begin{aligned} G_x &= \frac{\partial \rho}{\partial x}, \\ G_y &= \frac{\partial \rho}{\partial y} \end{aligned} \tag{2.9}$$

where u and v are the east-west and north-south advectons (equation 4.2.2). The gradients of FADs in zonal and meridional directions are G_x and G_y , respectively, and the gradients are standardized with $|G|_{max}$. The variable $|G|_{max}$ is the maximum of all absolute FAD gradients over the model domain and duration of a tagging experiment. The advective coefficient parameter is denoted by ψ .

FAD-Diffusion Model

The diffusion (D) variable in the traditional ADR model is theoretical and does not consider factors that can influence dispersive movements. FADs tend to reduce the propensity for tuna to leave the area (*Kleiber and Hampton 1994*). To include this in the FAD-Diffusion model, the diffusion component of tuna's movement is reduced to reflect the hypothesis that the density of FADs inhibits their movement. Two sub-models describing the influence of FAD density of diffusion are considered.

First, the exponential FAD-Diffusion model assumes that diffusion decreases exponentially from maximum diffusion (D_{max}) with increasing FAD density (ρ):

$$D = D_{max}e^{-\gamma\rho} \quad (2.10)$$

where D_{max} is the maximum of D and γ is the diffusion reducing rate, which is the parameter being considered in the model.

Second, in the logistic FAD-Diffusion model, diffusion decreases logistically from the maximum with increasing ρ . Three parameters are introduced into the model: D_{min} is the minimum diffusion when FAD density reaches its maximum (ρ_{max}); s is the rate of decreasing diffusion by FAD; and K is the density of the FAD that corresponds to the largest change in diffusion. The model is described as follows

$$D = L + \frac{U - L}{1 + e^{s(\rho - K)}} \quad (2.11)$$

where L and U are the lower and upper asymptotes of the logistic function. The asymptotes are

than reparameterized with the D_{max} from the traditional ADR model and the parameter D_{min} ;

$$\begin{aligned} U &= \frac{D_{min}(1 - B) - D_{max}(1 - A)}{A - B} \\ L &= \frac{A \cdot D_{max} - B \cdot D_{min}}{A - B} \end{aligned} \quad (2.12)$$

when A and B are

$$\begin{aligned} A &= \frac{1}{1 + e^{s(\rho_{max} - K)}} \\ B &= \frac{1}{1 + e^{-K}}. \end{aligned} \quad (2.13)$$

In both FAD-D models, the diffusion is reduced by increased FADs density. However, the two models are designed to have different ways of decreasing diffusion. The exponential FAD-D model has a rapid decrease in D (Figure 2.1) and the logistic FAD-D model shows sigmoid reduction in D (Figure 2.2). The logistic FAD-D model was designed to estimate the minimum diffusion (D_{min}) while the exponential FAD-D model sets the lower diffusion limit to 0. Because the diffusion cannot be 0, the logistic FAD-D model may more reasonable, however, it has higher variance because it has more parameters. Each of the two FAD-Diffusion models were run separately with the FAD-Advection model and the better model was chosen to use for the data fit.

2.1.3 Numerical Solution

The numerical solution used in this study is a finite difference method that uses a regular grid with a spatial resolution of 1° and a discrete time step of one month. The finite difference approximation used for the time derivatives is

$$\frac{\partial N}{\partial t}_{i,j,n} \simeq \frac{N_{i,j,n+1} - N_{i,j,n}}{\Delta t} \quad (2.14)$$

where i, j indicate the spatial location of a grid point ($i\Delta x, j\Delta y$) and n refers to the time level $n\Delta t$. The diffusion movement part of the derivative in equation (4.2.2) is approximated using three-point finite differences

$$\begin{aligned}
\frac{\partial}{\partial x} \left(D \frac{\partial N}{\partial x} \right)_{i,j,n} &\simeq N_{i-1,j,n} \frac{D_{i-1,j} + D_{i,j}}{2(\Delta x)^2} - N_{i,j,n} \frac{D_{i-1,j} + 2D_{i,j} + D_{i+1,j}}{2(\Delta x)^2} + N_{i+1,j,n} \frac{D_{i,j} + D_{i+1,j}}{2(\Delta x)^2} \\
\frac{\partial}{\partial y} \left(D \frac{\partial N}{\partial y} \right)_{i,j,n} &\simeq N_{i,j-1,n} \frac{D_{i,j-1} + D_{i,j}}{2(\Delta y)^2} - N_{i,j,n} \frac{D_{i,j-1} + 2D_{i,j} + D_{i,j+1}}{2(\Delta y)^2} + N_{i,j+1,n} \frac{D_{i,j} + D_{i,j+1}}{2(\Delta y)^2}
\end{aligned} \tag{2.15}$$

The advective movement of equation (4.2.2) uses approximation by two-point ‘‘backward’’ differences, known as ‘‘upwind’’ differencing. Upwind differencing of the directed movement terms at time level n takes the form of:

$$\begin{aligned}
\frac{\partial(uN)}{\partial x_{i,j,n}} &\simeq \begin{cases} \frac{u_{i,j}N_{i,j,n} - u_{i-1,j}N_{i-1,j,n}}{\Delta x} & u_{i,j} > 0 \\ \frac{u_{i+1,j}N_{i+1,j,n} - u_{i,j}N_{i,j,n}}{\Delta x} & u_{i,j} < 0 \end{cases} \\
\frac{\partial(vN)}{\partial y_{i,j,n}} &\simeq \begin{cases} \frac{v_{i,j}N_{i,j,n} - v_{i,j-1}N_{i,j-1,n}}{\Delta y} & v_{i,j} > 0 \\ \frac{v_{i,j+1}N_{i,j+1,n} - v_{i,j}N_{i,j,n}}{\Delta y} & v_{i,j} < 0 \end{cases}
\end{aligned} \tag{2.16}$$

To complete the numerical approximation for the partial differential equation for the model, the finite difference approximations (equation 2.15, 2.16) are substituted into the movement terms.

The approximations for zonal and meridional FAD density gradients for the FAD-advection model are approximated by central space difference method.

$$\begin{aligned}
\frac{\partial \rho}{\partial x} &\simeq G_{x_{i,j,n}} = \frac{\rho_{i+1,j,n} - \rho_{i-1,j,n}}{2\Delta x} \\
\frac{\partial \rho}{\partial y} &\simeq G_{y_{i,j,n}} = \frac{\rho_{i,j+1,n} - \rho_{i,j-1,n}}{2\Delta y}
\end{aligned} \tag{2.17}$$

The alternating direction implicit (ADI) method was used to solve the ADRM. The method is very robust and converges to an unconditional solution for all step sizes (*Carnahan et al.* 1969; *Press et al.* 1990).

2.1.4 Parameter Estimation

The predicted number of tags returned at point (i, j) by fleet f at time n is given by

$$\hat{C}_{ijnf} = \beta_f F_{ijnf} N_{ijn} = \beta_f q_f E_{ijnf} N_{ijn} \quad (2.18)$$

where β_f is the reporting rate (i.e., the proportion of tags captured by fleet f returned with usable recapture information), F_{ijnf} is fishing mortality from equation 4.2.4, q_f is the catchability coefficient for fleet f , E_{ijnf} is the fishing effort reported by fleet f from position (i, j) at time step n , and N_{ijn} satisfies equation 4.2.2 for time step n . Observed numbers of tag returns, C_{ijnf} , are related to predicted number of tag returns, \hat{C}_{ijnf} , by a Poisson likelihood. It assumes that the predicted number of tag returns in each unit area during one month is the expected value of a random variable with a Poisson distribution. This distribution is appropriate for the observation of a rare event or the recapture and return of a tagged fish,

$$\mathcal{L}(\theta|C, E) = \prod_{ijnf} \frac{\hat{C}_{ijnf}^{C_{ijnf}} e^{-\hat{C}_{ijnf}}}{C_{ijnf}!} \quad (2.19)$$

where $\theta = (u, v, D, q, M, \psi, \gamma)$ for the FAD-D exponential model, or $\theta = (u, v, D, q, M, \psi, D_{min}, s, K)$ for the FAD-D logistic model. The model parameters are estimated by reducing negative log likelihood function:

$$\begin{aligned} \hat{\theta} &= \arg \min_{\theta \in \Theta} l(\theta) \\ l(\hat{\theta}|C, E, \rho) &= -\log \mathcal{L} \end{aligned} \quad (2.20)$$

where Θ is the domain of the model parameters expressing upper and lower bounds. The AD Model Builder (*Fournier et al.* 2012) was used to perform the minimization process, which is based on a quasi-Newton numerical function minimizer. The minimizer is set to stop when the gradient of the stationary point of a function is smaller than 10^{-2} .

2.2 Data

2.2.1 Tagging Data

The Secretariat Pacific Community-Oceanic Fisheries Program (SPC-OFP) has conducted two large-scale tagging programs in the Western and Central Pacific Ocean (WCPO) since 1990's. Around this time, use of FADs was adopted widely by the purse seine fishery. The Regional Tuna Tagging Project (RTTP, 1989-1992) was conducted to provide useful data for stock assessment of skipjack and yellowfin tuna in the WCPO. The geographic area of the RTTP is restricted to the western tropical Pacific (Table 2.1). A total of 98,401 skipjack tuna were released and 12,695 (12.9%) of them were recaptured (Figure 4.2).

The Pacific Tuna Tagging Programme (PTTP) began in 2006 and is currently in progress. The objectives of the PTTP are to collect data for stock assessment and obtain information on tuna movement and mixing in the equatorial WCPO. The PTTP also aims to understand the impact of FADs on the movement of tuna. The target species of the programme are skipjack, yellowfin, and bigeye tuna. The PTTP covers a similar latitudinal range as RTTP but covers a wider longitudinal range. A total of 243,495 skipjack tuna were released and 40,071 (16.4%) were recaptured by Dec 2013 (Figure 4.3). Tag release data contains information on the number of fish released in a one-degree geographic square every month. The tag recapture data from the two programs contain the nationality of the captured fleet and fishing method in one-degree geographic resolution by month.

2.2.2 Fishing Effort Data and the Solution for Effortless Tag Data

All fishing vessels operating in the WCPO are required by treaty of the WCPFC convention to report their fishing effort to the Western and Central Pacific Fisheries Commission (WCPFC). The fishing efforts are reported by month and include position with the fleet information (nationality, fleet types). The fishing effort data are essential for the estimation process in the model (equation 4.2.4 and 2.18).

Tags are occasionally reported from positions and dates for which no fishing effort has been reported. The rate of “effortless” tag recapture has increased with the increase in the prevalence of purse

seiners (Table 2.2). The causes of no fishing effort are not clear but there are several possibilities: 1) simple error in recording dates and positions; 2) delays in reporting fishing effort; 3) tag recovered under circumstances where it is difficult to infer the date and position of recapture, such as from the well of a purse seiner at unloading.

When there is no reported fishing effort ($E_{ijnf} = 0$), the predicted number of tags (\hat{C}_{ijnf}) is set to zero (equation 2.18). Effortless recapture has no direct effect on the likelihood. Nevertheless, lack of fishing effort has an indirect effect on the likelihood through the population of tags at liberty. The effortless recaptures cannot be removed from the population because fishing mortality is computed to be zero (equation 4.2.4). The number of tagged fish remaining at liberty, N_{ijn} , is inflated which causes \hat{C}_{ijnf} also be inflated. This can result in estimates of M that are biased upward and estimates of q_f (equation 4.2.3) biased downward. There are three options to accommodate the condition of effortless recaptures: 1) effortless recaptures are ignored; 2) fishing mortality is set to the value required to produce the observed tag recaptures given the population density of tags using the inverse of the catch equation 2.18 ($F_{ijnf} \approx \frac{C_{ijnf}}{\beta_f N_{ijn}}$); 3) fishing effort is assumed to be equal to the average fishing effort \bar{E}_f for each fleet ($F_{ijnf} \approx q_f \bar{E}_f$).

To find the best solution for effortless recapture in the model, a simple test was conducted with three options where the effort of one fishing fleet was removed deliberately. Effort data of the United States of America purse seine (USPS) were excluded to generate an artificial effortless condition. The USPS effort has a moderate number of effortless recapture (not shown here). For this project, 300 simulations were run for each option under the artificial effortless condition. The parameters were estimated from simulations under the three options and compared to the estimations with USPS effort (standard). The PTTP data are used in this test. The model domain covers 120°E-170°W and 15°S-10°N. The duration of the model is from the time the first tag was released (August 2006) to 12 months after the last tag was released (March 2009). The effort data used in the test are seven nationalities of purse seiner that have more than 100 recaptures in the domain area. The simulation results are shown in Table 2.3. The estimations of fishing effort are relatively similar under the three options. All the effort estimations from three methods were close to the standard. Estimations of natural mortality (M) from the three options are higher than the estimation from

standard, as expected. Overall, the estimations from omit are closest to the standard estimations. Therefore, the ‘omit’ option was used to handle effortless returns.

2.2.3 FAD Data

The information on purse seine sets is used as a proxy for FAD density because real data on FAD numbers and positions are not available for the WCPO. When a purse seiner reports the fishing information, it includes date, time of starting sets, geographic position, and type of set (unassociated set or associated set). The purse seine fishing data were provided by SPC-OFP for the study. The data contains reported associated purse seine sets from 1979 to recent, which is the entire fishing history of purse seine using floating objects in the WCPO. The total set positions ($\hat{\rho}$) in each computational element (1° square) (i, j) in month n are used in this study (equation 4.2.1) as a proxy for FAD density (ρ).

$$\rho_{ijn} \simeq \sum \hat{\rho}_{ijn}. \quad (2.21)$$

2.3 Model Verification

2.3.1 Heuristics

The FAD sub-models are formulated to restrict or stimulate fish movement depending on the density of FAD (ρ). The tag (tuna) movement simulator (*tagmove*) is designed to show how the model moves tagged fish around. Figure 2.5a shows the FAD densities at one time step during the simulation. The color scale indicates the density of FADs in the unit area ($1^\circ \times 1^\circ$) at the time step. Figure 2.5b is the movement field during the same time step as Figure 2.5a. The color scale indicates diffusion and each arrow displays the advection in the unit area at the time step. The areas with higher density of FADs have lower diffusion than neighboring areas. The figures show the arrows are moving toward the areas that have higher FAD density. The snapshot shows that the graphic simulation, *tagmove*, is consistent with the model.

2.3.2 Process of Testing Parameter Estimability

To test the parameter estimability of the ADR-FAD model, the sets of simulation and estimation (Figure 2.6) were run using skipjack tuna tag release data from PTTP. If the model is effective, it should be able to estimate model parameters from the base data. The process of running a set of the simulation and estimation test is as follows.

1. Adequate values ("true parameters") for each parameter are fed into *tagmove*, the tag movement simulator, by equation 4.2.2 - 4.2.5, and either 4.2.7 or 2.11. During the simulation, FAD density field changes at each time step (month).
2. *Tagmove* (simulator) generates "the simulated tag recaptures" including geographic position, date, and fleet based on the true parameters.
3. The simulated tag recaptures are set as "observed tag recaptures," and use in the tag movement estimator, *tagest*. *tagest* estimates the all parameters by equation 2.19 and 2.20 through the model run using the monthly FAD density field.

The set of the simulation and estimation can be repeated as many times as needed. Each simulation gets different simulated tag recaptures, which is caused by multiple realizations of the random process. Therefore, the estimated parameters from each set of simulation and estimation are different. The estimated parameters from the all sets are then compared with the true parameters. Ultimate goal of the process is to have the estimated parameters are close to the true parameters.

2.3.3 Data Dependency

Ideally, the model domain should include most of the tag release and recapture positions to maximize the use of the data. However, fisheries data in the exclusive economic zone (EEZ) of the Philippines and Indonesia are sparse. Because fisheries data are an essential input for the model, two different model domains were investigated for potential issues arising from the sparse data. The first, "small domain", consists of the main purse seine fisheries ground except the EEZ of the Philippines and Indonesia (Figure 2.7a, 15°S-10°S, 140°E-170°W). The second, "big domain", includes the small domain and the EEZ of the Philippines and Indonesia (Figure 2.7b 15°S-10°S,

120°E-170°W). Four simulations were tested with the two model domains and two different FAD sub-models (Table 2.4).

The value of true parameters used in the simulation are Table 2.5, 2.6. For each simulation, 500 sets of simulations and estimations were performed. The running period of the simulation is 54 months since the first month of tag release.

Most simulation tests on the big domains (S2 and S4) failed to converge, but most simulation tests on the small domains (S1 and S3) did not converge (Table 2.4). As a result, regions with insufficient data (i.e. the part of the big domain outside the small domain) were excluded from the model domain. Two models are plotted based on the simulation tests using the small domain (S1 and S3) (Figure 2.8). The curves for the logistic FAD-D model are not encouraging because the estimated curves are variable. The reasons for the unstableness could be: 1) the FAD data cannot support the model; 2) the model itself is wrong; or both 1) and 2). Both FAD sub-models are highly dependent on the FAD data. In FAD-D sub-models, FAD density in unit area (ρ) is the strongest influence on the models. The density is concentrated narrow distribution; $<5 \text{ FAD}/1^{\circ 2}$ are more than 50% of density distribution (Figure 2.9). In the logistic FAD-D model, the estimation of K (the inflection point) is not possible because of the lack of data points. In simulation S1, estimations of K were biased lower than the true value. The exponential FAD-D model has a simple exponential decay of diffusion, therefore, it showed better estimability in the simulation. The results of the simulation test are: 1) the models can converge; 2) models are sensitive to the base data (i.e., fishing effort data); and 3) the FAD-D exponential model clearly showed better estimation ability than FAD-D logistic model.

2.3.4 Estimability

The model was tested on its estimation ability for the FAD-parameters (γ for exponential FAD-D model; D_{min} , s , K for logistic FAD-D model). Each parameter was tested with different initial values in the small domain (Figure 2.7a). The design for the test is as follows: 1) simulated tag recaptures are generated from *tagmove* using true parameters (Table 2.8); 2) *tagest* is used to

estimate the target parameter from different initial values based on the simulated tag recaptures. Step 2 was repeated 300 times for each test. In each test, different initial values were selected from the range presented in Table 2.7 and used in the estimation. The estimation results for γ were very stable (Table 2.8). The interquartile range (IQR, the 3rd quartile - the 1st quartile) of estimated γ was 7.28×10^{-8} . The test for single parameter estimations showed similar results (T2-T4). The IQR from the 300 estimations was very small (Table 2.8). However, when the estimation test was applied for three parameters at once, the results were unstable. The results of the estimability tests imply the logistic FAD-D model is not as stable as the exponential FAD-D model.

2.3.5 Sensitivity Analysis

A sensitivity analysis is necessary to obtain reliable results from the model and also to test the robustness of the model. The FAD parameters (ψ , D_{min} , s , K for FAD-D logistic model; ψ , γ for FAD-D exponential model) were tested in relation to 1) the range of diffusion (D) and 2) the range of advection (u , v). When the movement parameters are fixed in the simulation, the FAD parameters change to fit to the variables. The diffusion parameters (D) used here were: 1) $3000 \text{ nm}^2/\text{month}$ ($1 \text{ nm}/\text{day}$); 2) $5000 \text{ nm}^2/\text{month}$ ($1.3 \text{ nm}/\text{day}$); 3) $10000 \text{ nm}^2/\text{month}$ ($1.9 \text{ nm}/\text{day}$); and 4) $20000 \text{ nm}^2/\text{month}$ ($2.7 \text{ nm}/\text{day}$). The advection parameters (u , v) are tested with 1) $0.5 \text{ nm}/\text{day}$, 2) $1 \text{ nm}/\text{day}$, 3) $2 \text{ nm}/\text{day}$, and 4) $4 \text{ nm}/\text{day}$. For each FAD sub-model, seven different sets of movement parameters were used for the simulation and estimation process (Table 2.9). Other parameters were chosen from the estimations by traditional ADR model and FAD parameters were chosen: natural mortality = 0.27; catchability coefficient for nine purse seines in a range of 0.0009-0.0126, $D_{min} = 500$; $s = 0.36$; $K = 5$; $\gamma = 0.36$. The running time of the simulations is 54 months since the first month of tag released (August 2006). The small domain (Figure 2.7a) was used for the analysis. For each simulation test, 500 sets of simulations and estimations were computed and the estimations of FAD parameters were compared.

For the logistic FAD-D model, the ranges for ψ and D_{min} gradually increased with the increase in D (Figure 2.10a, 2.10b). However, the range of s and K showed the opposite pattern (Figure 2.10c, 2.10d). The estimations of K for all diffusion tests have negative skewness. The median of

each simulation test consistently stayed near the true parameters (red dots). The ranges of ψ in the u, v simulations showed similar patterns with the results of ψ in the diffusion simulations (Figure 2.11a). The ranges of D_{min} did not change with the ranges in u, v . The estimations of s increased with the increase of u, v , and there was no consistent trend for K .

In the exponential FAD-D model test, the IQR of ψ gradually increased with the increase of true D (Figure 2.12a), while γ showed the opposite pattern. The estimation of ψ did not show any change with increasing u, v (Figure 2.13a), whereas the IQR of γ increased with increasing u, v (Figure 2.13b).

Overall, ψ showed the most consistent trend in the range of D and u, v change but there was a difference in scale. In the FAD-D logistic model, the parameters showed a clear pattern in the difference in D but not with u, v . In the FAD-D exponential model only parameter γ changed in an opposite manner with the changes in D and u, v .

2.4 Summary and Conclusion

This chapter describes the ADR-FAD model and verifies it by simulation tests. The ADR-FAD model is designed based on the attraction and hindering tendency of FADs to tuna. The advection and diffusion component in the model are controlled by FADs by following hypothesis: 1) the directional movement of tuna is forced by the gradient of FAD density, and 2) the diffusive movement of tuna is reduced with higher FAD density in two ways (exponentially and logistically). The ADR-FAD model was simulated using real tag data, fishing effort data, and FAD sets data. The simulation tests were run with several purposes. First, the model was tested under data limitation. Even though fisheries data is an essential input for the model, absence of data is occurring in the process of data collecting. When tags are recaptured without effort data, omitting them appears the best solution. Including areas with sparse fishing effort obstructs the estimability of the model. The FAD-D exponential model has better estimation ability than the FAD-D logistic model. Second, the technical ability of the model was tested in two points (estimability and sensitivity). When each parameter was tested with wide ranges of initial values, The FAD-D exponential model is more stable than the FAD-D logistic model because the FAD-D logistic model has more parameters than

the FAD-D exponential model. The FAD parameters' sensitivity were simulated in relation to the ranges of diffusion and advection. The estimations of the FAD-D logistic parameters are skewed and have more outliers than the estimations of the FAD-D exponential parameters. The fishery and tag data have limitations because of inevitable conditions even though it is essential to produce reliable results from the ADR-FAD model. More than 10,000 simulations were computed to find the better remedy under the data limitation. The model showed the best results when the less parameter model, the FAD-D exponential model, was applied the domain contains accurate data. The conclusion may sound a natural result but it is essential to confirm the model. The results will be applied in following two chapters to answer two hypotheses.

2 References

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Sibert, J. R., J. Hampton, D. A. Fournier, and P. J. Bills (1999), An advection–diffusion–reaction model for the estimation of fish movement parameters from tagging data, with application to skipjack tuna (*katsuwonus pelamis*), *Canadian Journal of Fisheries and Aquatic Sciences*, 56(6), 925–938.

Table 2.1: Summary of skipjack tag release and recapture data in two tagging programs.

	RTTP	PTTP
Period	1989-1992	2006-present
Target area	10°N-10°S, 140°E-180°	10°N-10°S, 120°E-130°W
Releases	98,401	243,495
Recaptures	12,695 (12.9%)	40,071 (16.4%)

Table 2.2: Historical development of effortless recaptures by programs. The numbers were counted in 140E-170W, 15S-10N.

	RTTP	PTTP
Without Effort	403	1980
With Effort	5389	15094
	7%	13%

Table 2.3: The means of some catchabilities by purse seine nations and natural mortality estimations from standard and three options for effortless recaptures (ID= Indonesia, JP=Japan, SB=Solomon Islands, US= The United State of America).

	IDPS	JPPS	SBPS	USPS	M
Standard	0.0029	0.0225	0.1015	0.0016	0.2765
Option 1. Omit	0.0030	0.0224	0.1018	0.0017	0.2772
Option 2. Inverse	0.0027	0.0226	0.1021	0.0017	0.2774
Option 3. Average E	0.0028	0.0224	0.1018	0.0017	0.2776

Table 2.4: Simulation sets

Simulation	Domain size	FAD-D model	Number of converged
S1	small	logistic model	500/500
S2	big	logistic model	3/500
S3	small	exponential model	500/500
S4	big	exponential model	55/500

Table 2.5: True parameters for natural mortality, catchability coefficients, and movement parameters. Catchability coefficients are concatenations of the country code and the gear code (i.e. JP=Japan, PS=purse seine). KR=Korea, PG=Papua New Guinea, SB=Solomon Islands, TW=Taiwan, US=United States.

Parameters		Value
natural mortality		0.15
catchability coefficient	JPPS	0.02656
	KRPS	0.00307
	PGPS	0.03657
	SBPS	0.07889
	TWPS	0.00283
	USPS	0.00876
u		1.0
v		1.0
D		20000

Table 2.6: True parameters for FAD parameters: (a) logistic model and (b) exponential model

(a) logistic model		(b) exponential model	
Parameters	Value	Parameters	Value
ψ	10	ψ	10
D_{min}	500	γ	0.36
s	0.36		
K	2		

Table 2.7: The true parameter and the range of initial values for (a) exponential model and (b) logistic model runs.

(a) exponential model			(b) logistic model		
Parameters	Value	Range	Parameters	Value	Range
γ	0.368	$4.5 \times 10^{-5} - 20$	D_{min}	500	$10^{-4} - 10^4$
			s	0.368	$4.3 \times 10^{-5} - 20$
			K	5	1 - 40

Table 2.8: Summary of test on parameter estimability.

Test	FAD-D model type	Target param.	True value	IQR
T1	exponential model	γ	0.36	7.28×10^{-8}
T2	logistic model	D_{min}	500	0.45
T3	logistic model	s	0.36	1.1×10^{-5}
T4	logistic model	K	5	1×10^{-5}
T5	logistic model	D_{min}	500	449.75
		s	0.36	0.508
		K	5	19.80

Table 2.9: Summary of simulations for sensitivity test.

Simulation	FAD-D model type	u (nm/day)	v (nm/day)	D ($nm^2/month$)
S1	logistic model	1	1	3000
S2	logistic model	1	1	5000
S3	logistic model	1	1	10000
S4	logistic model	1	1	20000
S5	logistic model	0.5	0.5	10000
S6	logistic model	2	2	10000
S7	logistic model	4	4	10000
S8	exponential model	1	1	3000
S9	exponential model	1	1	5000
S10	exponential model	1	1	10000
S11	exponential model	1	1	20000
S12	exponential model	0.5	0.5	10000
S13	exponential model	2	2	10000
S14	exponential modell	4	4	10000

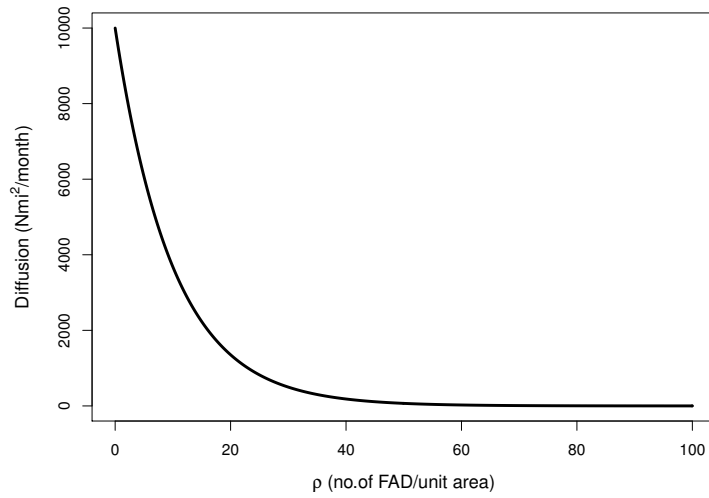


Figure 2.1: Plot of FAD-Diffusion exponential model (when $\gamma = 0.1$).

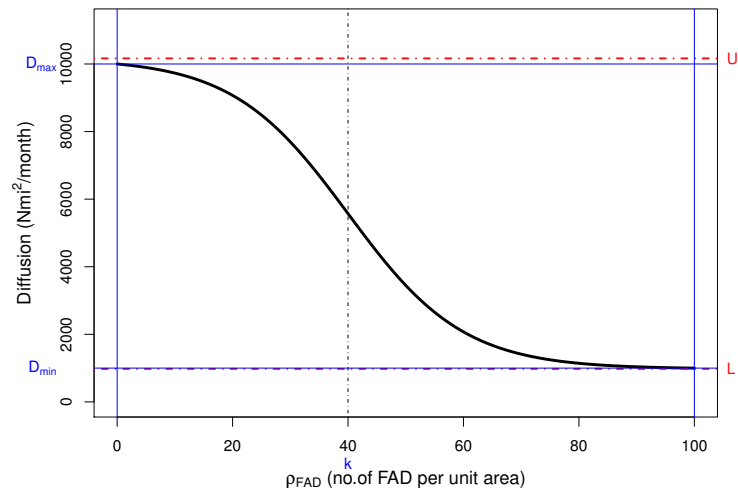


Figure 2.2: Plot of FAD-Diffusion logistic model (when $D_{min}=1000$, $s=0.1$, and $K=40$).

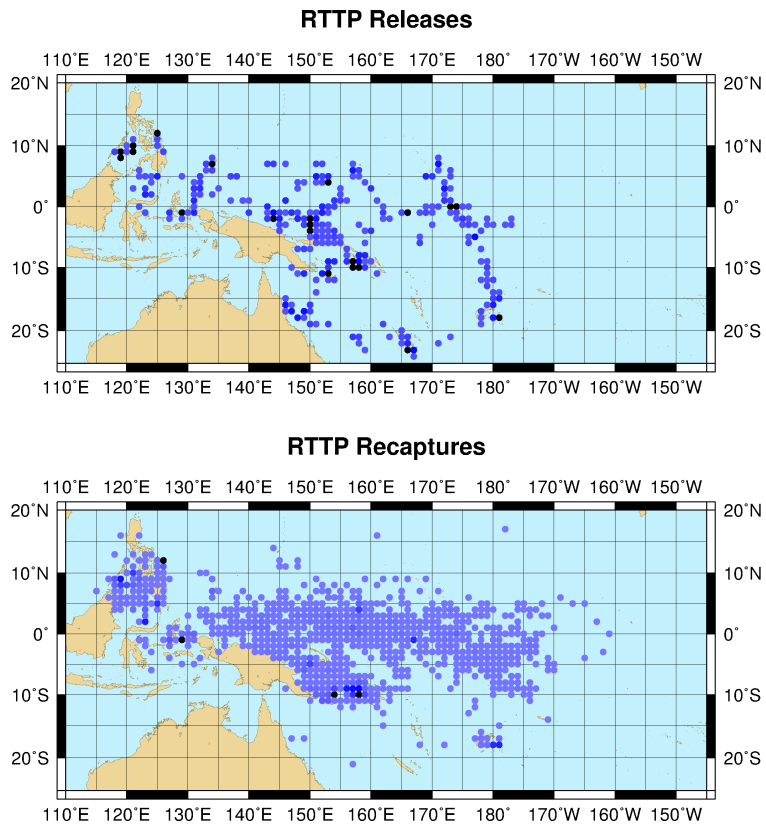


Figure 2.3: Maps of the WCPO with skipjack tag releases and recaptures during RTTP.

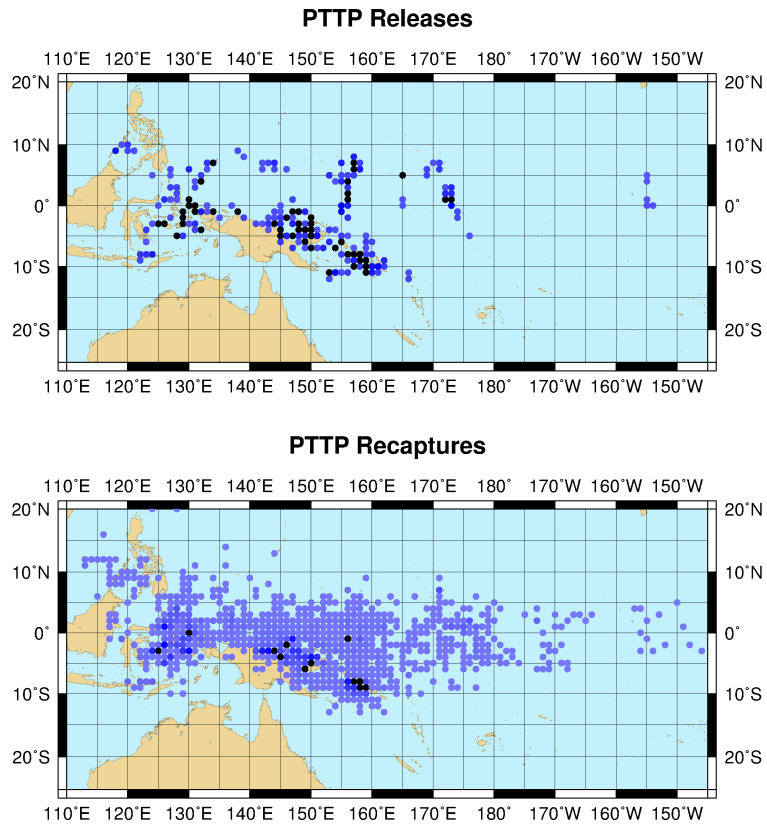
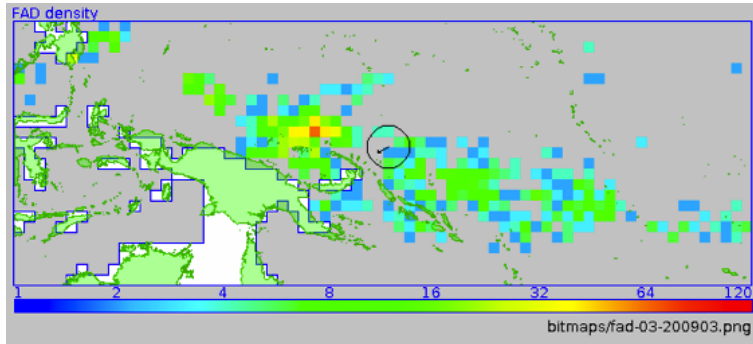
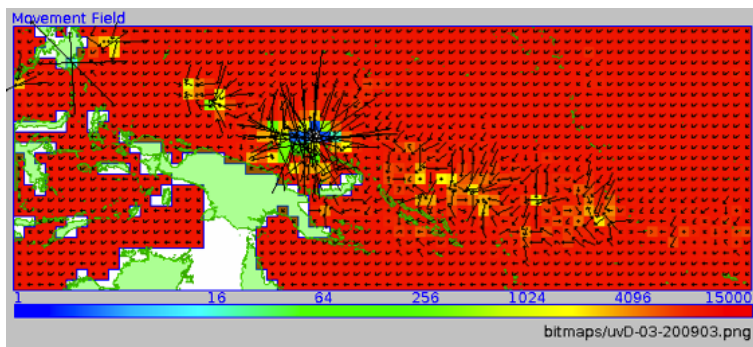


Figure 2.4: Maps of the WCPO with skipjack tag releases and recaptures during the first seven years of PTTP.



(a) FAD density



(b) Movement Field

Figure 2.5: A snapshot of logistic model simulation. (a) FAD density map with diffusion(D) in a circle. (b) Movement field (u, v) of tuna.

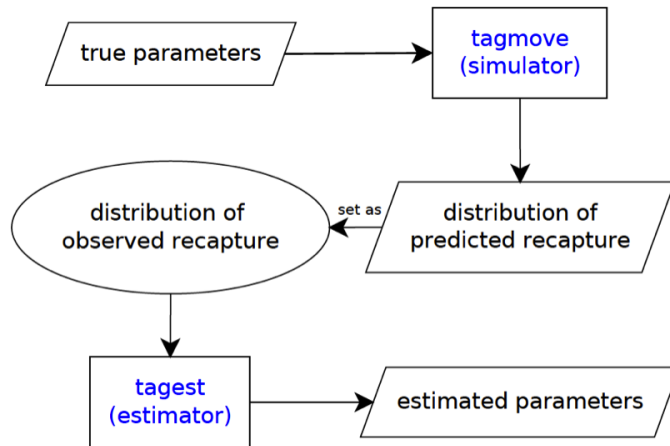


Figure 2.6: Schematic flowchart showing one set of simulation and estimation.

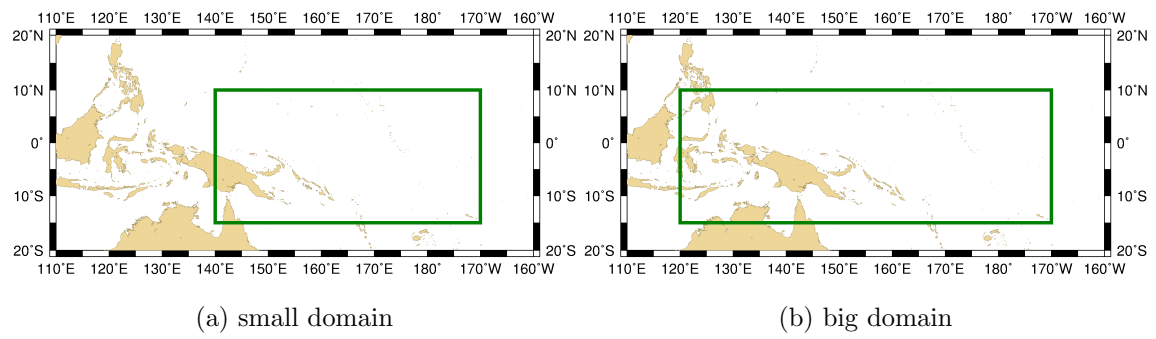
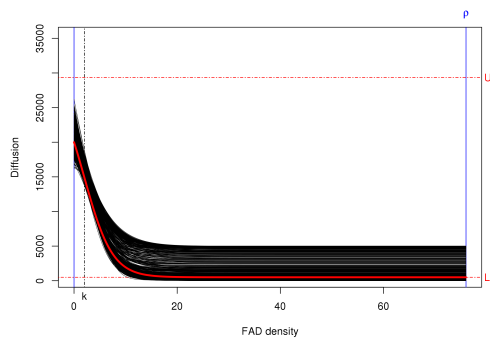
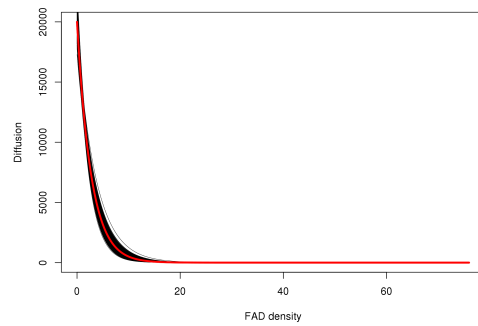


Figure 2.7: Two model domains for the regional simulation test



(a) logistic FAD-D model



(b) exponential FAD-D model

Figure 2.8: FAD-D model fits for simulations S1 and S3. The true curve (red) are plotted by the true parameters (Table 2.6). The black lines are the results of each simulation.

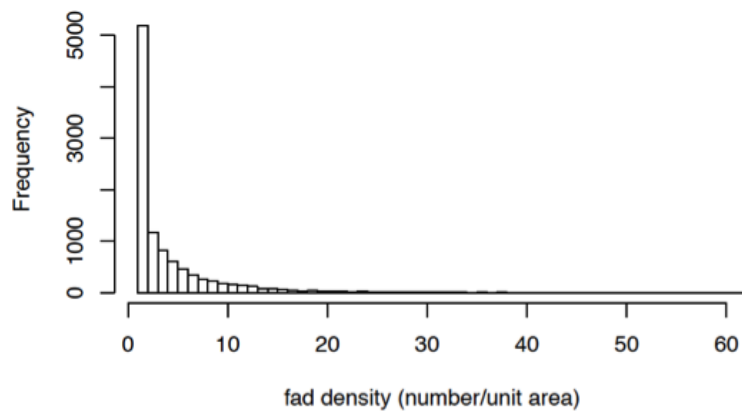
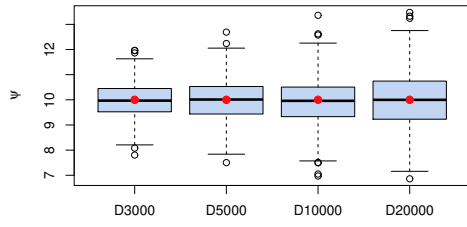
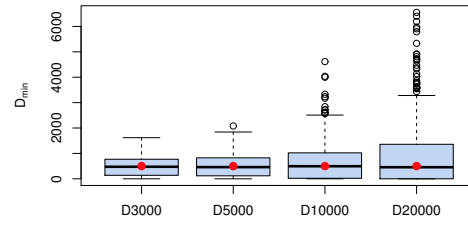


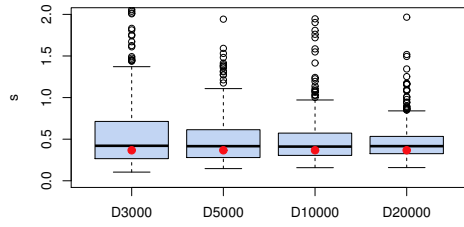
Figure 2.9: FAD density distribution used in the simulation.



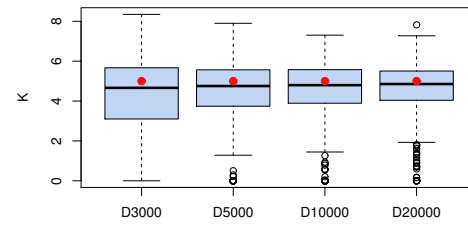
(a) $\hat{\psi}$



(b) \hat{D}_{min}

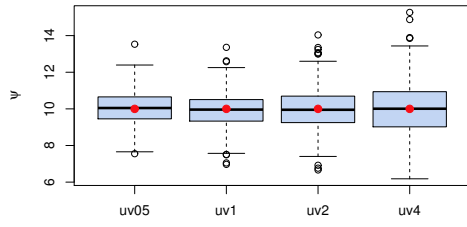


(c) \hat{s}

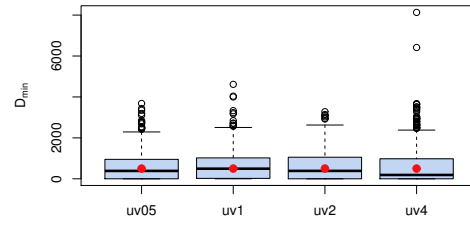


(d) \hat{K}

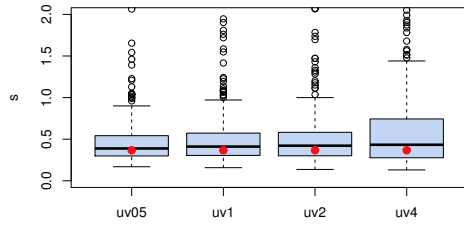
Figure 2.10: The results of ψ and the logistic model parameters by D variability. Each box indicates the range of the estimations of (a) ψ , (b) D_{min} , (c) s , and (d) K for S1 ($D=3000$), S2 ($D=5000$), S3 ($D=10000$), and S4 ($D=20000$). Red dots are the true values used for the simulations.



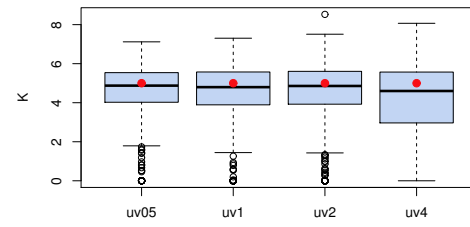
(a) $\hat{\psi}$



(b) \hat{D}_{min}



(c) \hat{s}



(d) \hat{K}

Figure 2.11: The results of ψ and the logistic model parameters by u, v variability. Each box indicates the range of the estimations of (a) ψ , (b) D_{min} , (c) s , and (d) K for S5 ($u, v=0.5$), S3 ($u, v=1$), S6 ($u, v=2$), and S7 ($u, v=4$). Red dots are the true values used for the simulations.

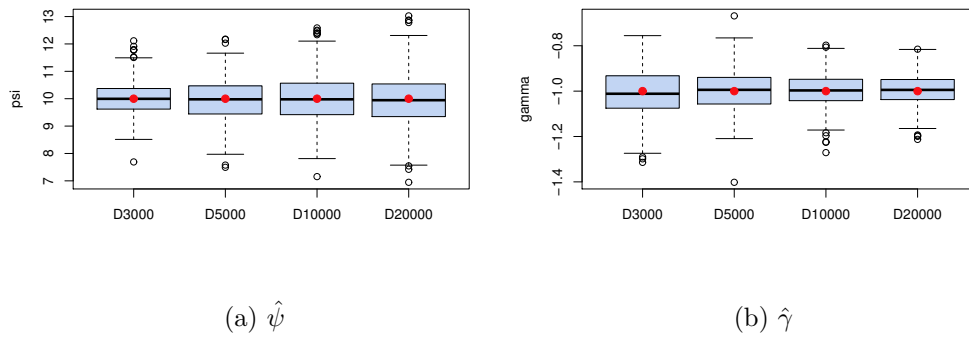


Figure 2.12: The results of ψ and the exponential model parameters by D variability. Each box indicates the range of the estimation of (a) ψ and (b) γ for S8 ($D=3000$), S9 ($D=5000$), S10 ($D=10000$), and S11 ($D=20000$). Red dots are the true values used for the simulations.

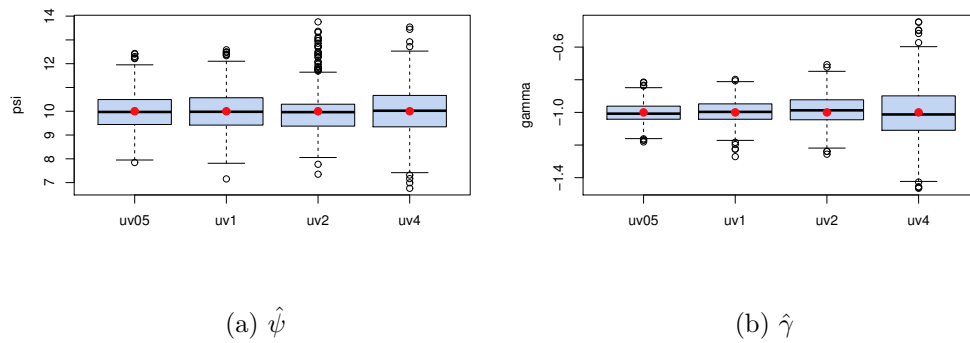


Figure 2.13: The results of ψ and the exponential model parameters by u , v variability. Each box indicates the range of the estimations of (a) ψ , (b) γ for S12 ($u, v=0.5$), S10 ($u, v=1$), S13 ($u, v=2$), and S14 ($u, v=4$). Red dots are the true values used for the simulations.

CHAPTER 3

MOVEMENT OF SKIPJACK TUNA (*KATSUWONUS PELAMIS*) IN RELATION TO FISH AGGREGATING DEVICES (FADS) USING THE ADVECTION-DIFFUSION-REACTION-FAD MODEL.

3.1 Introduction

Tuna and many other pelagic fish associate with objects drifting on the ocean surface, such as logs and branches, in the open ocean. This characteristic of tuna allows fishing vessels, especially purse seiners, to quickly locate and catch them because an associated school is easier to find than a free swimming school. Searching and operating on floating objects has clear advantages in the purse seine fishery (*Dagorn et al.* 2013). It reduces the search time for tuna schools because they are clearly visible. Once floating objects are found, purse seiners can track them easily by attaching radio buoys, GPS, and transmitters. Less time and fuel is spent for searching for tuna schools. Fishing using floating objects allows increased fishing success rates. Schools associated with floating objects are usually less mobile than free swimming schools. Consequently, sets on associated schools have higher success rate (90%) than sets on unassociated, free swimming, schools (*Fonteneau et al.* 2000; *Suzuki et al.* 2003; *Miyake et al.* 2010). These advantages led fishers to rapidly build and use artificial fish aggregating devices (FADs), and soon the use of FADs became the dominant method in tropical tuna purse seine fishing since the 1990's (*Miyake et al.* 2010).

Despite the widespread use of FADs, our understanding of the mechanisms, such as how tuna detect the FADs, how far they can detect the FADs, how long tuna stay under FADs, and why they are attracted by FADs, is limited. Sound has been suggested as a potential attraction for tuna to the FADs. *Ghazali et al.* (2013) found that underwater sound signal of a FAD was detectable from 1000m away. However, the result is far shorter than tuna detection distances (9-13 km) from various studies (*Holland* 1990; *Cayré* 1991; *Marsac and Cayré* 1998; *Girard et al.* 2004). Many of these studies are conducted by tracking individual fish around FADs. Most recent studies on tracking tuna around FADs (*Matsumoto et al.* 2014; *Schaefer and Fuller* 2013) followed 15 to 85

individual around drifting FADs in the Pacific. These studies found that highly variable resident time and swimming patterns around FADs for tracked fish. Tracking individual fish can collect detailed information on their movements, however, it has the limitations on the detection range and tracking time because of the detection range and the limitation of battery in transmitters. Therefore, results are hard to generalize at population levels for application in the management of FAD usage on tuna fisheries.

A half of the worldwide skipjack catch is made around floating objects in four major oceans (Atlantic, Indian, Eastern Pacific, and Western and Central Pacific) (*Dagorn et al.* 2013)). The Western and Central Pacific Ocean (WCPO) produces the largest tuna catch in the world. The WCPO has complicated boundaries due to the many exclusive economic zones (EEZs) of Pacific states and high seas (Figure 3.1). In addition to complicated boundaries, a diverse range of fisheries from small-scale artisanal fisheries to large-scale industrial fisheries are operating in the region. Since 1980, the tuna species in the WCPO have been studied and monitored by the Ocean Fisheries Programme (OFP) of the Secretariat of the Pacific Community (SPC). The OFP activities include tuna fisheries research, fisheries monitoring, stock assessment and data management. In 2006, the Pacific Tuna Tagging Programme (PTTP), which is a joint project by the SPC-OFC and the PNG National Fisheries Authority (NFA), was conducted to improve stock assessment and management of tuna species in the Pacific Ocean (*Nicol et al.* 2010). The PTTP is the largest tagging study since the massive use of FADs started in 1990s. During the program, three major tuna species, skipjack, yellowfin, and bigeye tuna, were tagged and released in more than 300 locations in the WCPO.

Unlike the Lagrangian movement models which are based on random walk behavior of individuals, Eulerian models focus on the change of probability of the animal's density or occurrence through time at a given space. Eulerian models describe the expected patterns of animal distribution which are averaged over the study area, and often are applied to test research questions on the population (*Smouse et al.* 2010). The ADR model is a typical Eulerian movement model for tuna species. The ADR model estimates the movement, fishing, and natural mortality of a tuna population from the spatial and temporal changes in population (tag) density (*Sibert et al.* 1999; *S. Adam and*

Sibert 2002; *Sibert and Hampton* 2003). The movement is partitioned into directed (advection) and dispersive (diffusion) components. This study adds attraction and hindering tendency of FADs to the advection and diffusion components of the Advection-Diffusion Reaction (ADR) model. Earlier work on the effects of FAD components in population-scale movement model (*Kleiber and Hampton* 1994) found FADs can reduce the propensity of skipjack to leave the area by 50% around the Solomon Islands. Since that study, the distribution of FADs is much wider and more dynamic because of the prevalence of drifting FADs.

In this study, 1) to determine including FAD data can improve the ADR model, the ADR model and the ADR-FAD model are applied to the skipjack conventional tag data from PTTP ; 2) to compare the influence of FADs in open and coastal ocean, the ADR-FAD model was applied in the two-regional domains. Understanding the geographic difference on FAD effects is important not only for the utilization of FADs in fisheries but also for the management of their usage. Any regional differences in the effects of FADs may imply the difference of anchored FADs and drifting FADs since anchored FADs are dominant in the coastal ocean and drifting FADs are common in the open ocean.

3.2 Materials and Methods

3.2.1 Data

Tagging Data

Skipjack conventional tagging data from PTTP were provided from SPC. The tagging dates ranged from August 2006 to June 2013, and recovery dates from August 2006 to September 2013. The tagging releases mainly occurred in the range 120°E-175°E, 15°S-10°N and the tags were widely recaptured (Figure 3.2). Till the end of 2013, a total of 243,495 tags were released during seven trips using commercial pole-and-line vessels. By March 2014, 40,071 tags were recaptured from the commercial fisheries. For this study, tag releases between August 2006 to July 2011 and tag recaptures between August 2006 and December 2012 were extracted from the PTTP data to coincide with the available fishing effort data. The recaptures with a positional accuracy of equal

or less than 1° were extracted by the reliability of its position and time of each recapture. 59% of tag recaptures (22,815) matched this criterion. “Effortless” were resolved according to procedures described in Appendix 3.A.

Fishing Effort Data

Purse seine effort data of nine nationalities were provided from SPC. The fishing effort data by the number of sets were stratified by 1° square and calendar month for the period of August 2006 to December 2012. The nationalities of the purse seiners (flags) that caught sufficient numbers of tags (≥ 200) in the model area were chosen for the study. The flags were: Federated State of Micronesia (FM); Korea (KR); Papua New Guinea (PG); Philippines (PH); Solomon Islands (SB); Taiwan (TW); United States of America (US); Vanuatu (VU); and Japan (JP).

For each flag, a different reporting rate was used to avoid systematically underestimating fishing mortality and overestimating natural mortality. *Berger et al.* (2014) estimated the reporting rates of each flag by tag seeding experiments by observers aboard purse seiners of different flags throughout the WCPO between 2007 to 2012. These rates were applied in this study (Table 3.1).

FAD data

Fishing information on purse seine sets is used as a proxy for FAD density because real data on FAD numbers and positions are not available. Purse seiners reported date, start time, geographic position, and type of a set (unassociated set or associated set). The geographic positions of associated sets from drifting natural logs, man-made raft, and anchored raft in the period of 2005-2013 were used as a proxy for FAD distributions. The count of associated set positions in each computational element (1° square at i, j) in each computational step (month n) (Equation 4.2.1) is used as a proxy for FAD density.

$$\rho_{ijn} \simeq \text{count}(\text{set}_{pqt} | p = i, q = j, t = n) \quad (3.1)$$

3.2.2 Model Description

Model Domain

Model domain was chosen as follows: 1) exclude the Philippines and Indonesia EEZ because the region has sparse fisheries data; 2) include the main purse seine fishing ground; and 3) include as many tag release sites as possible. The model domain includes 15°S-10°N and 140°E-170°W (Figure 4.4). Within the model domain, two different regional sections were applied (Figure 4.4); 1) whole domain as one region, and 2) two regional sections of coastal and open ocean.

Advection-Diffusion Reaction Model(ADR Model) with FAD-Sub Models

The Advection-Diffusion Reaction model (ADR model) estimates the movement and mortality of a fish population using tagging data (*Sibert et al.* 1999). Movement is represented by an advection-diffusion process, which is the equivalent for population in biased random walk of individual movement (*Okubo and Levin* 2001). The model is based on the number of tagged fish. The number of tagged fish per unit area satisfies the following partial differential equation that shows the local rate of change of tag density (N) at a point (x, y) :

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial N}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial N}{\partial y} \right) - \frac{\partial}{\partial x} (uN) - \frac{\partial}{\partial y} (vN) - ZN \quad (3.2)$$

On the right side of equation 4.2.2, the first two terms describe dispersive movements in terms of ‘diffusion’ parameter D . The second two terms characterize directed movement in terms of ‘advection’ parameters u, v that describe east-west and north-south movement, respectively. The last term describes the loss of tagged fish by fishing and natural mortality. Total mortality (Z) is defined by

$$Z_{xyt} = M + \sum_f F_{xyt}f \quad (3.3)$$

where $F_{xyt}f$ is the mortality due to fishing by fishing fleet f operating at point (x, y) during time step t and natural mortality M . The natural mortality is assumed to be constant at all times and

locations. Fishing mortality is assumed to be a simple function of observed fishing effort

$$F_{xyt f} = q_f \cdot E_{xyt f} \quad (3.4)$$

where $E_{xyt f}$ is the observed fishing effort of fleet f operating at point (x, y) during time step t and q_f is a catchability coefficient, which indicates a fleet specific proportionality constant of fish catch by a unit of fishing effort.

The Advection-Diffusion Reaction FAD model (ADR-FAD model) includes two sub-models FAD-Advection and FAD-Diffusion. The FAD-Advection model is based on the simple rule that tuna in a region with lower FAD density move toward a neighboring region with higher FAD density. In the model, the FAD density gradients control the directional movement of tuna along with their ‘natural’ movement in the model. The total advection (u, v) is the algebraic sum of the natural movement (u_r, v_r) and the movement induced by FADs $(\psi \cdot \frac{G_x}{|G|_{max}}$ and $\psi \cdot \frac{G_y}{|G|_{max}})$ when ψ is the swimming speed caused by FADs:

$$\begin{aligned} u &= u_r + \psi \cdot \frac{G_x}{|G|_{max}}, \\ v &= v_r + \psi \cdot \frac{G_y}{|G|_{max}} \end{aligned} \quad (3.5)$$

when

$$\begin{aligned} G_x &= \frac{\partial \rho}{\partial x}, \\ G_y &= \frac{\partial \rho}{\partial y} \end{aligned} \quad (3.6)$$

where u and v are the east-west and north-south advections (equation 4.2.2). The gradients of FADs in zonal and meridional directions are G_x and G_y , respectively, and the gradients are standardized with $|G|_{max}$. The variable $|G|_{max}$ is the maximum of all absolute FAD gradients over the model domain and duration of a tagging experiment. The advective coefficient parameter is denoted by ψ .

Diffusion in the ADR model is relevant to a random walk in Lagrangian models, which allows

to disperse or spread animals in the model. The diffusion (D) itself in the traditional ADR model is theoretical and does not consider factors that can influence dispersive movements. In the FAD-Diffusion model, the diffusion component of movement is restricted by the density of FADs. The FAD-Diffusion model assumes the diffusion decreases exponentially from maximum diffusion (D_{max}) with increasing FAD density (ρ):

$$D = D_{max}e^{-\gamma\rho} \quad (3.7)$$

where D_{max} is the maximum of D , and γ is the diffusion-reducing rate.

Closed boundary conditions are used for this study. Fish cannot move out of the boundaries, which means that no fish can move out of the model domain. Hence, at the boundaries

$$\begin{aligned} u &= 0, \\ v &= 0, \end{aligned} \quad (3.8)$$

and,

$$\begin{aligned} \frac{\partial N}{\partial x} &= 0, \\ \frac{\partial N}{\partial y} &= 0. \end{aligned} \quad (3.9)$$

These conditions ensure that tagged tuna numbers stay in the model domain when fishing and natural mortalities are zero. The initial condition for N is

$$N_{xy0} = \begin{cases} \sum_c \tilde{N}_{x_c y_c 0_c}, & \text{tag release sites,} \\ 0, & \text{elsewhere.} \end{cases} \quad (3.10)$$

where $\tilde{N}_{x_c y_c 0_c}$ is the number of tagged fish released at point (x_c, y_c) at time 0 in tag cohort c . A cohort here is defined as total tagged fish released in a one-degree geographic square at time t . Therefore, $\tilde{N}_{x_c y_c t_c}$ is the density of tagged tuna at point (x, y) in the ocean at time t of tag release cohort c . The aggregated density of tagged tuna (N) from all cohorts released up to time t is given

by

$$N_{xyt} = \sum_{c=1}^{c_t} \tilde{N}_{x_c y_c t_c}. \quad (3.11)$$

3.2.3 Numerical Solution

See Chapter 2

3.2.4 Parameter Estimation

See Chapter 2

3.2.5 Model Comparison

The likelihood-ratio test is used to compare the relative goodness-of-fit between the ADR model and ADR-FAD model (*Huelsenbeck et al.* 1996). The test compares the fit of a more complex model, the ADR-FAD model, to that of a simpler model, the ADR model, to determine if the additional complexity is justified by a significant improvement in fit. The test statistic for conducting a likelihood ratio test is

$$LR = 2 \log \frac{\mathcal{L}_1}{\mathcal{L}_0} \quad (3.12)$$
$$LR = 2(\log \mathcal{L}_1 - \log \mathcal{L}_0)$$

where $\log \mathcal{L}_1$ is the likelihood of the ADR-FAD model and $\log \mathcal{L}_0$ is the likelihood of the ADR model. Under the null hypothesis that there is no improvement in the fit, the likelihood ratio statistic follows the chi-square distribution,

$$LR \sim \chi_{n_1 - n_0}^2 \quad (3.13)$$

where n_1 is the number of parameters in the ADR-FAD model and n_0 is the number of parameters in the ADR model. The difference between the number of parameters is the degree of freedom for

the chi-square statistic.

3.3 Results

3.3.1 ADR vs ADR-FAD model

The estimations for the fishing mortalities and the natural mortality in both models are very similar while the estimations for the movement parameters have some differences (Figure 3.4). The Japanese purse seine (JP) shows the highest fishing mortality among the nine purse seine fleets in both models. The estimates of total fishing mortality (F) and natural mortality (M) were almost identical for the two models. The advection are resolved into east-west (u) and north-south (v). The advective parameters are south ($v > 0$) - west ($u < 0$) for both models with variance. The plotted u, v for the ADR-FAD model is the natural movement (u_r, v_r) in Figure 3.4. The total advection is decided by the natural movement (u_r, v_r) and the movement induced by FAD gradients (ψ). The estimate for ψ is 11.91 Nmi/day , which is much higher than $u_r, v_r < 0.4 Nmi/day$. The advection is dominated by the FAD induced movement.

Figure 3.5 is the plot of FAD-Diffusion model (equation 4.2.7) using estimated D_{max} and γ . The half-diffusion density ($\rho_{1/2}$), the FAD density where has the half reduction in the maximum diffusion, is 6.3 FAD per one degree square.

The predicted recaptures were simulated based on each set of estimations and were visualized with the observed recaptures in Figure 3.7. The simulated tag recaptures from the two models resemble each other. However, in some cells (1° square) that have a higher number of observations, i.e., north of PNG, the predicted recaptures from the ADR-FAD model is in better agreement with the number of observations. Both two models could not predict the recaptures in the far east cells. Figure 3.6 shows the tag recaptures within the study time. The predicted recaptures from the two models (ADR, ADR-FAD(g1)) are very similar. The predicted tag recaptures from both models don't reach the sharp peaks of the observed tag returns especially in the first three years (2007-2009). The root mean square (RMS) of two models in tag returns are very close (RMS_{ADR}

= 134.1, $RMS_{ADR-FAD_{g1}} = 133.49$), but the difference became larger since 2010 ($\Delta RMS = 4$).

The likelihood ratio test ($LR = 260.64$, $df = 2$, $P < 0.001$) shows that the ADR-FAD single region model was significantly better than the ADR model.

3.3.2 Application of ADR-FAD model in coastal and open ocean

The estimated natural mortality and fishing mortality by fleets are shown in Table 3.2. The natural mortality for skipjack is 0.22/month and the fishing mortalities are in the range of 0.013-0.0008/month. The mortality estimations are close to the estimations from single regional ADR and ADR-FAD model (Figure 3.4).

Table 3.3 shows the estimated movement parameters for two regions: region 1 (coastal region) and region 2 (open ocean) (Figure 4.4). In the natural movement in both regional sections, the west and east movement (u_r) is higher than the north and south movement (v_r). The estimation for the movement induced by FAD gradient (ψ) in the open ocean were 4 times higher than that in the coastal ocean. In both regions, the contribution of FAD gradients to movement (ψ) is higher than the natural movement (u_r, v_r). The FAD-Diffusion model (equation 4.2.7) are plotted using the results of the estimation in Figure 3.8. The diffusion reduced more rapidly in the coastal region than in the open ocean. The half-diffusion density ($\rho_{1/2}$) were smaller in the coastal region than $\rho_{1/2}$ in the open ocean. The predicted tag recaptures of ADR-FAD two regions model are similar with other two models (Figure 3.6). However, it had the lowest RMS among them ($RMS_{ADR-FAD_{g2}} = 131.9$). The likelihood ratio test between the single region model and two regions model found that the effect of sectioning is significant ($LR=2307.68$, $df=5$, $P < 0.001$).

3.4 Discussion

Including FAD information into the traditional ADR model improved the estimation of skipjack tuna movement patterns. The improvement was the most significant when the ADR-FAD model was applied into two regional sections; the open and coastal ocean. The effect of FADs on tuna movement was more pronounced in the open ocean compared to the coastal ocean. The open ocean likely presents fewer objects, such as land or island, to hinder FAD detection by tuna. The ψ

was estimated in between 5.6-28.4 Nmi/day, which can be converted to 12.0-60.8 cm/sec. This is a reasonable speed of skipjack tuna considering the size range of tagged fish (Figure 3.9) (*Yuen* 1966). The diffusion-reducing rate (γ) in the open ocean is smaller than that in the coastal region which implies that the effect of FADs on skipjack's movement is more an advective process in the open ocean. The results indicate that the increasing density of FADs in the open ocean, mostly drifting FADs, may more easily establish an 'ecological trap' (*Marsac et al.* 2000). The ecological trap hypothesis states that FADs could take fish to areas where they would not normally go or hold them in places where they would normally leave. *Dagorn et al.* (2010) did not find any differences in tuna's behavioral process for drifting and anchored FADs. Even though the types of FADs are not distinguished in the model, the FADs in the open ocean are mostly drifting FADs. Therefore, the difference in FAD parameters between the open and coastal ocean suggests differing behavior processes driving the association of tuna with drifting and anchored FADs.

The proxy FAD density used in the study is the minimum density. The total number of FAD in the whole model domain area was 1277 on average, which is 1 FAD/ $1^{\circ 2}$. However, recent information on the FAD in the WCPO indicates that the total number of FAD may be over 30,000 (*Scott and Jon* 2014). When FADs are normally distributed in the region, the average density is 24 FAD/ $1^{\circ 2}$. It is 24 times more than the proxy used. The half-diffusion density was estimated to be 1.1-6.3 FAD/ $1^{\circ 2}$ which can convert to a radius of 25.5-62.6 km per a FAD. This is much longer than the previous studies on the effect ranges of *Girard et al.* (2004). However, when the estimated half-diffusion density multiplied by 24 times, the radius range becomes 5.2-12.7km per a FAD. This is in agree with *Girard et al.* (2004).

The estimates of natural mortality (M) from all three model fits are higher than other studies (*Rice et al.* 2014) on skipjack in the same region. The higher estimates are attributable to several causes. In tagging experiments, some loss of tags is inevitable (*Skomal* 2007). The tag failure includes tag-induced post-release mortality and tag shedding (*Hoyle et al.* 2015). Tuna tagging experiments in this study used pole-and-line methods. The hooked fish was lifted into the boat by hook, measured and tagged before being released back to the ocean. The process imposed some degree of stress so the fish is probably more vulnerable than one that didn't go through

tagging process. *Gaertner and Hallier* (2014) estimated tag shedding rates for skipjack tuna at 0.7% and 2.9% for short and long term, respectively. The rate of tag shedding and mortality or other effects by tagging are not explicitly defined in this model, but rather collectively accounted for by natural mortality. The model did not consider the size of fish, even though natural mortality is size dependent (*Rice et al.* 2014). The size range of tagged skipjack during PTTP is wide (Figure 3.9). Skipjack caught by pole and line and purse seine have a much smaller size range than skipjack caught by longline. More than 90% of tagged skipjack are caught by purse seine during PTTP. In this study, only using purse seine data may contribute to a high estimate of natural mortality.

More than 50% of skipjack are caught from associated sets (by weight). The proportion of associated catch was over 60% before the start of FAD closure of the high seas and EEZ of the Parties of Nauru Agreement (PNA) in 2009 (CMM2008-01, *Hampton and Harley* (2010)). After the FAD closure, it was reduced to 50% (figure 3.10). The effect of the FAD closure cannot be identified in this study. However, the restriction on purse seine fishing grounds caused a clustering of FAD distribution around the closure area, and it may explain the better agreement between observed recaptures and simulated recaptures after 2010 (Figure 3.6). The absence of recaptures in part of the high seas observed could be due to FAD closure as well (Figure 3.11).

Previous studies tried to understand tuna's movement in relation to FADs (*Kleiber and Hampton* 1994; *Dagorn et al.* 2007; *Schaefer and Fuller* 2010, 2013), but most of them has limited on the number of FAD (≤ 100). These studies did not find consistent conclusion on the effects of FADs. One of the problems caused by the prevalence of FADs is the high catch on juvenile yellowfin and bigeye tuna. To reduce their catch, the FAD closures through high seas and EEZ are implemented in the WCPO since 2009. The catch of bigeye tuna were reduced during the closure periods (*Hampton and Williams* 2011), but the effectiveness of the closure is still questionable (*Sibert et al.* 2012). More studies should be conducted to investigate how the effects of FADs in the larger scale since tuna fishing ground is not restricted in a small scale, how these effects differ between the regions by the number of FADs for better management and regulation on the usage of FADs in tuna's fisheries.

Appendix

3.A Recalculation on Tag Data and Application

The issue on effortless tag recaptures is discussed in Chapter 2.2. The effortless recaptures cannot be removed from the model population because there is no fishing effort in the data for these recaptures. Therefore, the number of effortless recaptures causes the estimation of catchability to be biased downward. Another problem with the effortless recaptures is that the estimation of natural mortality is biased upward. To avoid the problem caused by effortless recaptures, they were ignored in recaptures. Some of tags were reported without proper information such as date or location of the catch, or both. These tags are excluded in recaptures with effortless recaptures. The number of tags released (R') used in the model was modified based on the neglected recaptures (r_n), which is the sum of effortless recaptures and uninformed recaptures (equation 3.A.1, 3.A.2). The proportion of tag recovery (the total number of releases (R)/the total number of recaptures (r)) was maintained between the number of releases (R') and the number of recaptures (r') for each tag release position to prevent biasing the fishing mortality

$$R : r = R' : r', \quad (3.A.1a)$$

$$R' = \frac{Rr'}{r} \quad (3.A.1b)$$

when

$$r' = r - r_n \quad (3.A.2a)$$

Before the application of the recalculation process, the total releases are reduced by 58.7%, which is the ratio of recapture data used in this study. Then the number of release for each position was reduced by equation 3.A.1, 3.A.2. The total releases and recaptures were reduced

to 87,857 and 15,094. The ignored recaptures caused by insufficient information was 192 and the effortless recaptures were 1980. The ratio between the release and recapture changed to 0.17 which is very close to the ratio in raw data (0.16). Total release events are reduced from 329 to 309 because tag recaptures from 20 of the tag release events were mostly invalid recaptures.

3 References

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Table 3.1: Estimated reporting rate for purse seine vessels by flag. Adapted from (*Berger et al.* 2014)

Flag	Reporting rate
PH	0.80
PG	0.81
SB	0.98
JP	0.23
VU	0.69
TW	0.65
US	0.60
FM	0.32
KR	0.40

Table 3.2: Estimates of natural mortality, fishing mortalities by purse seine fleets and total mortality.

parameter	estimation	std
M	0.224	0.0035
JP	0.0131	0.00047
PG	0.0051	0.00009
PH	0.0028	0.00006
US	0.0028	0.00018
FM	0.0026	0.00019
SB	0.0014	0.00003
KR	0.0014	0.00012
TW	0.001	0.00007
VU	0.0008	0.00005
total M	15.3	0.0038

Table 3.3: Estimations of movement parameters and FAD parameters in two regions.

	coastal (g1)	open (g2)
u_r	-1.78	1.17
v_r	-0.15	-0.53
ψ	5.6	28.4
D_{max}	32160.4	35303.1
γ	0.61	0.34
$\rho_{1/2}$	1.13	2.02

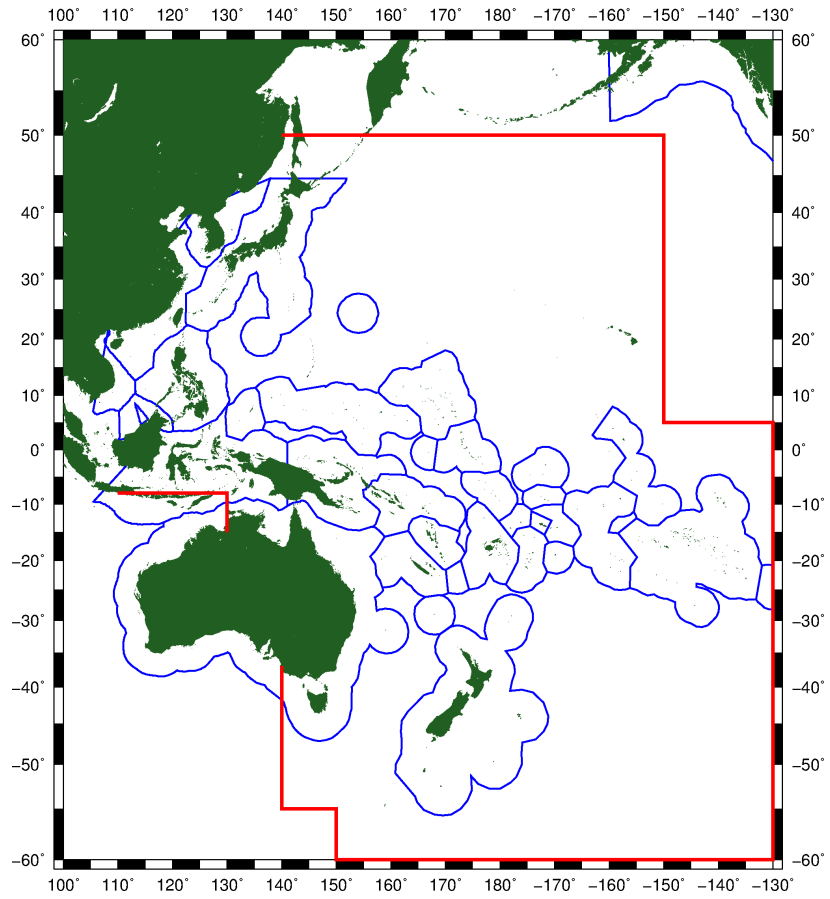


Figure 3.1: The Pacific Ocean, showing the EEZs in blue line and the boundary of the WCPFC area in red.

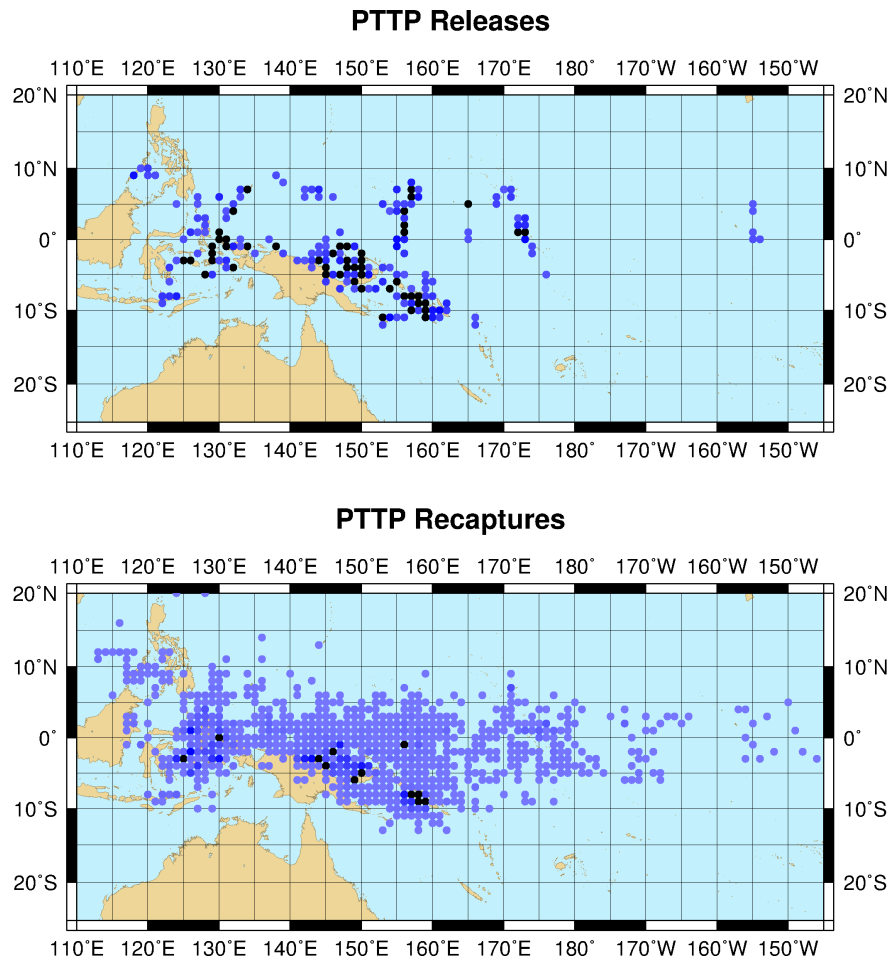


Figure 3.2: Maps of the PTTP tag releases and recaptures during 2006-2013. The number of releases and recaptures are expressed with colors.

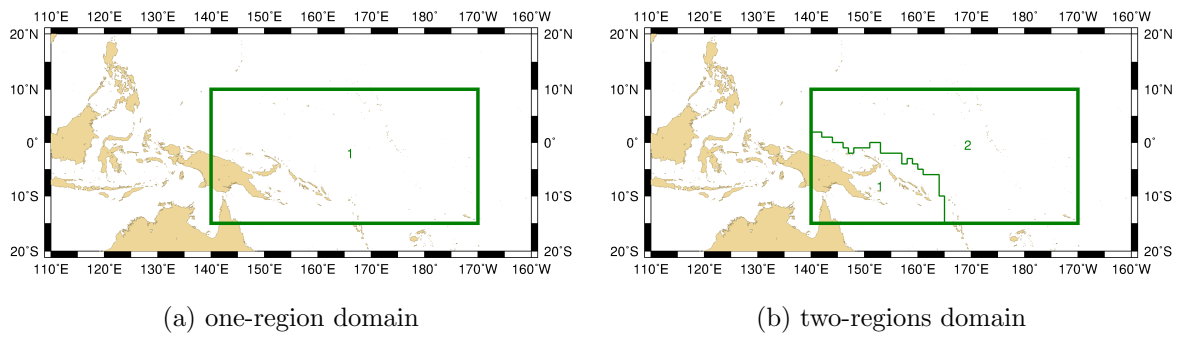


Figure 3.3: Two types of model domain sections

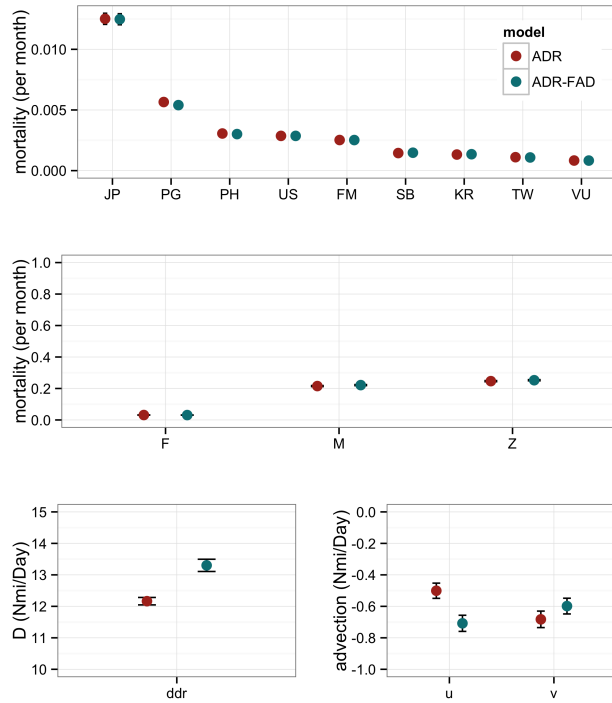


Figure 3.4: Estimated parameters from the ADR and ADR-FAD models for the PTTP skipjack data. Estimated fishing mortality by fleet, total fishing mortality (F), natural mortality (M), total mortality (Z), daily diffusive rate (ddr), and advection (u, v) over the model domain from two models are plotted with colored dots. The error bars are 1 standard deviation.

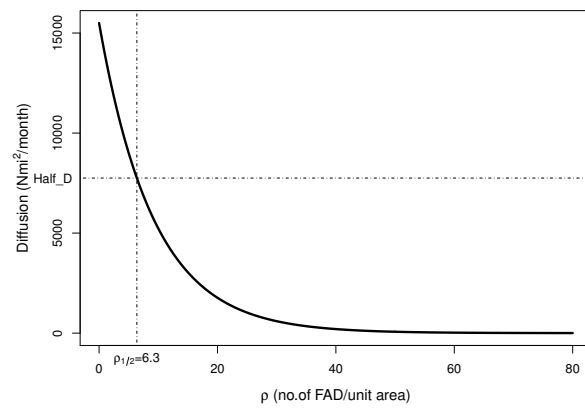


Figure 3.5: FAD-D model plot with estimated parameters: $D_{max} = 15501$, and $\gamma = 0.108$. The density for the half diffusion ($\rho_{1/2}$) is 6.3.

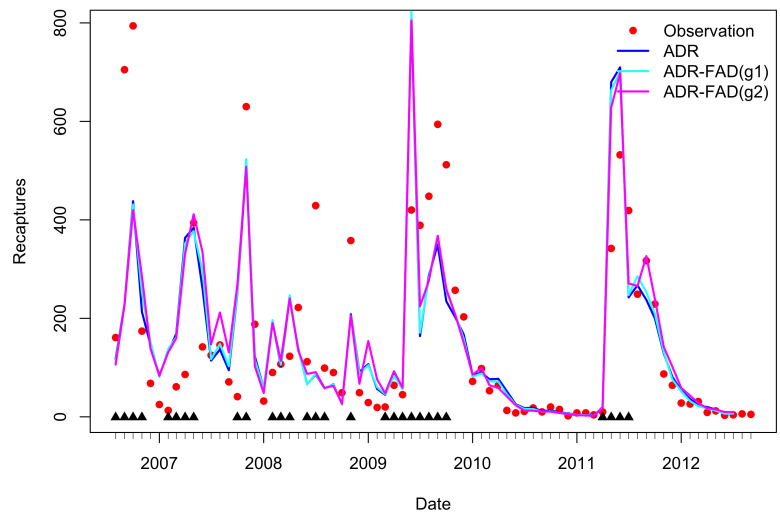
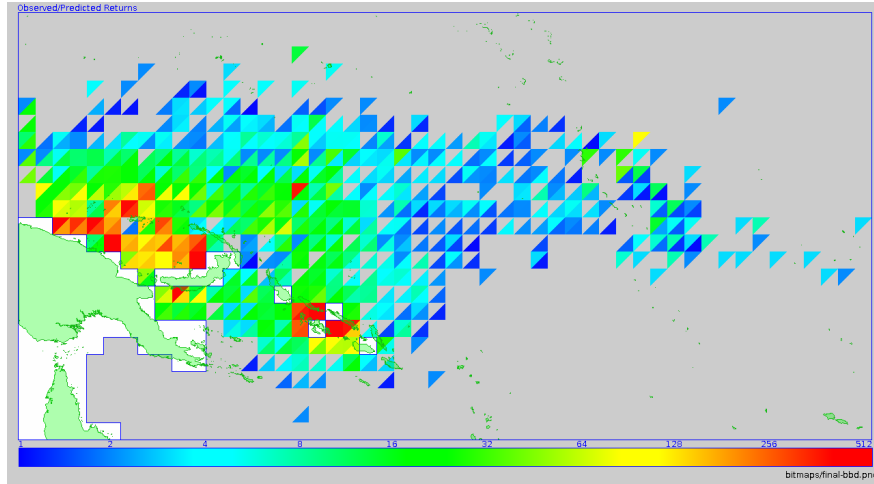
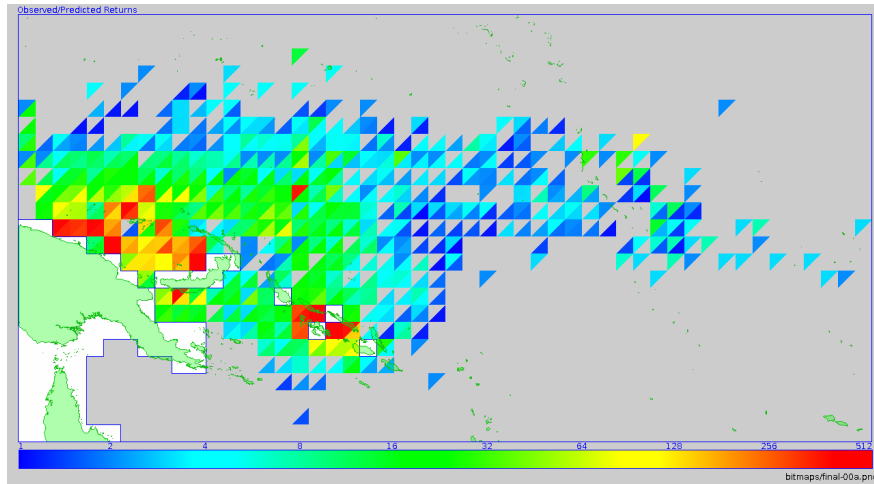


Figure 3.6: Observed (symbols) and three predicted (solid line) tag returns over the study time. Small black triangles are the months of tag releases.



(a) ADR model



(b) ADR-FAD model

Figure 3.7: The spatial distribution of observed and predicted tag returns by (a) ADR model and (b) ADR-FAD model. Each cell has two triangles: the upper left triangle indicates the number of observed recaptures and the lower right triangle indicates the number of predicted recaptures.

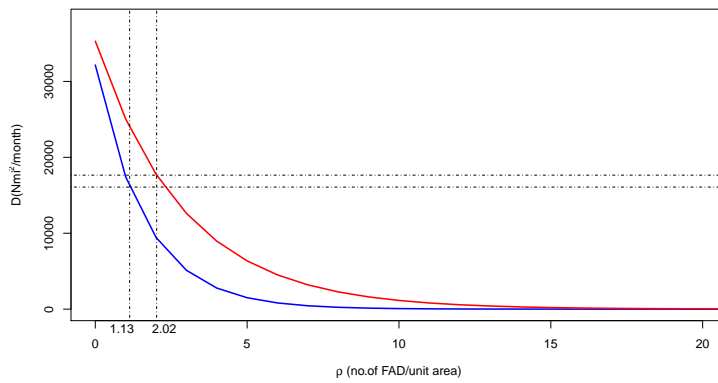


Figure 3.8: FAD-D model plots for coastal (blue) and open (red) oceans from estimated parameters in Table 3.3.

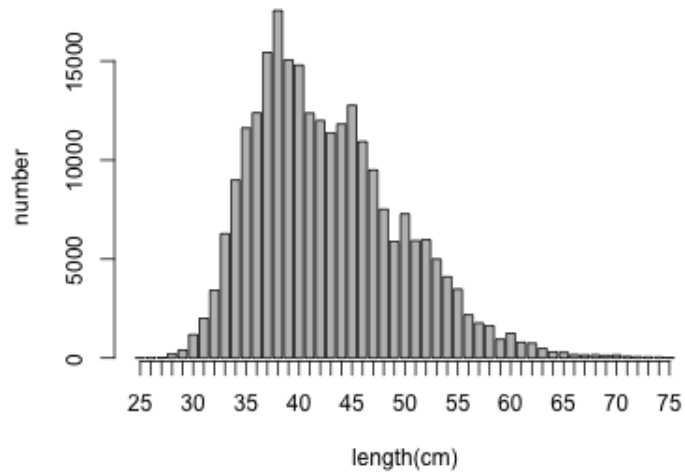


Figure 3.9: Size-frequency distribution of skipjack released during PTPP. Fork length (cm) in bottom axis and number of released in left axis.

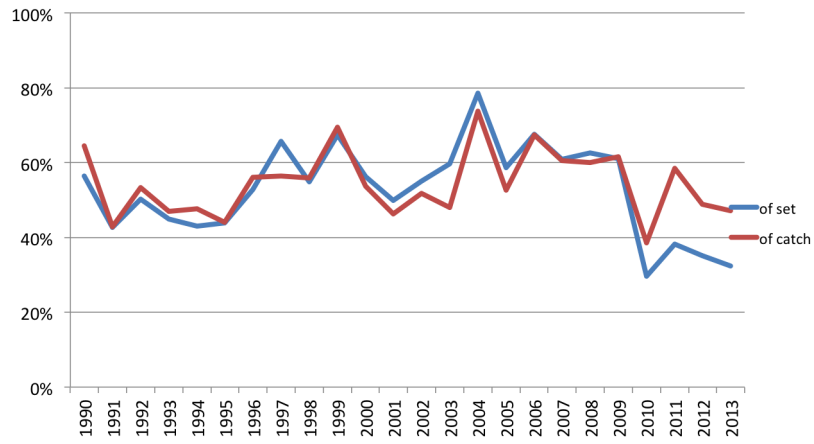


Figure 3.10: Proportion of FAD associated sets and catch for skipjack to the total catch in the WCPO.

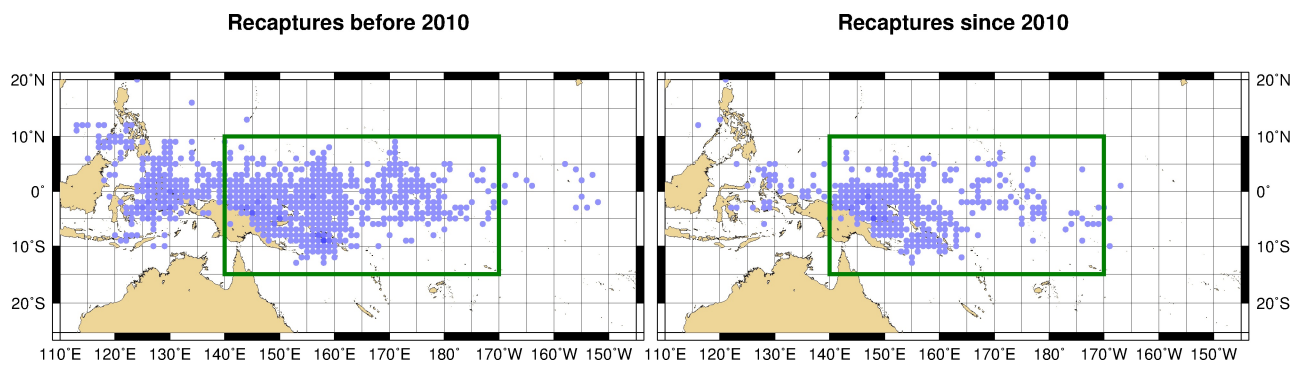


Figure 3.11: Recaptures distribution before and after the FAD closure in the high sea. The green boxes indicate the model domain.

CHAPTER 4

DID THE PROLIFERATION OF FADS CHANGE THE MOVEMENT OF SKIPJACK?

4.1 Introduction

The use of fish aggregating devices (FADs) is ubiquitous in modern purse seine fisheries. The term ‘FAD’ refers to any type of man-made object built for use in the fisheries, while the term ‘log’ refers to any natural debris. The term ‘floating objects’ includes both the FAD and log. In the Western Central Pacific Ocean (WCPO) the use of FADs started to expand in the early 1990’s. Searching and operating on floating objects has clear advantages in the purse seine fisheries (*Dagorn et al.* 2013). Searching for floating objects takes less time because they are easily identifiable by sight. With FADs, purse seiners can track them easily by attaching tracking devices, such as radio buoys, GPS, and transmitters. It allows the fleets to spend less fuel and time for searching tuna schools. Also, fishing using floating objects allows increased fishing success rates. Schools associated with floating objects are usually less mobile than free swimming schools. Consequently, sets on associated schools have a higher success rate (90%) than sets on free swimming schools (*Fonteneau et al.* 2000; *Suzuki et al.* 2003; *Miyake et al.* 2010). These advantages led fishers to rapidly adopt FADs, and by 2000, the use of FADs has become the dominant method in tropical tuna purse seine fishing (*Miyake et al.* 2010).

FADs were hypothesized to alter the movement of tuna in several studies (*Marsac et al.* 2000; *Hallier et al.* 2008). To understand the effects of FAD on the movement of tuna, many studies were designed to track individual fish around FADs using a sonic or satellite tags (*Cayré* 1991; *Dagorn et al.* 2007; *Schaefer and Fuller* 2010, 2013). Tracking individual fish allows us to collect the detail information of each fish such as horizontal and vertical movement, behavior and environmental data. However, individual-based information is highly variable and inappropriate in spatiotemporal scales for fisheries management. Individual tracking is expensive and hard to scale up to fish populations for useful inferences in management practices. Therefore, population models and simulation applications offer a better alternative. With the approach, the spatial

scale can expand to ocean-basin scale, and the temporal scale can extend to years to match the requirements for management measures evaluation. Therefore, I applied the Advection Diffusion Reaction FAD model (ADR-FAD model) to two large-scale tagging programs in the WCPO: the Regional Tuna Tagging Project (RTTP, 1989-1992) and the Pacific Tuna Tagging Programme (PTTP, 2006-present). The RTTP period corresponds to the wide expansion of equatorial purse seine and the adaption of FADs by these purse seine fleets, whereas the PTTP was conducted after FADs were more widely and commonly used by purse seiners.

The Western and Central Pacific Fisheries Commission (WCPFC) implemented conservation and management measures (CMM) to reduce the fishing mortality of bigeye and maintain the fishing mortality of yellowfin tuna. The CMM includes the closure of purse seine fishing in association with FADs in high seas waters of the conservation areas from August 2009 (*Anonymous* 2014). The duration of the closure lasted for two months (August to September) at the beginning but, currently, it has been extended to three months (July to September) since 2013.

The model results were compared to find the difference in their movements and the FAD effects on the movement of the skipjack population. The results show that the natural advective movements changed and maximum diffusive movement reduced 25% between the two periods. Also, the advective movements induced by FADs increased significantly in the recent tagging data, which may imply an anthropogenic influence on skipjack populations in the WCPO.

4.2 Materials and Methods

4.2.1 Data

Tagging Data

Skipjack conventional tagging data were provided from the Secretariat Pacific Community-Oceanic Fisheries Program (SPC-OFP). The Regional Tuna Tagging Programme (RTTP, 1989-1992) was conducted between 120°E-170°W and 10°N-10°S (Figure 4.1) (*SPC* 1993). A total of 98,401 tags were released and 12,695 (12.9%) of them were recaptured from the commercial fisheries. All release and recapture data were included in this study (Figure 4.2). The Pacific Tuna Tagging

Programme (PTTP, 2006-present) has the same latitudinal range as RTTP but covers a broader longitudinal range (Figure 4.1). Till the end of 2013, a total of 243,495 tags were released and 40,071 (16.4%) tags were recaptured. For this study, tag releases between August 2006 to July 2011 and tag recaptures between August 2006 and December 2012 were extracted from the PTTP data to coincide with the available fishing effort data (Figure 4.3). All recaptures from two tagging programs with a positional accuracy of equal or less than 1° were extracted by the reliability of its position and time of each recapture. 80% and 59% of tag recaptures from each program remained after applying this criterion.

Fishing Effort Data

Purse seine and pole and line effort data were provided by the SPC. The fishing effort data by the number of sets were stratified by 1° square and calendar month from July 1989 to December 1994 (RTTP) and from August 2006 to December 2012 (PTTP). For the RTTP, three fleets of pole and liners and six fleets of purse seiners were included while nine fleets of only purse seiners were chosen for the PTTP (Table 4.1). Different reporting rates were used to avoid systematically underestimating fishing mortality and overestimating natural mortality for each fleet in a tagging program (Table 4.1).

FAD Data

Fishing information on purse seine sets is used as a proxy for FAD density because real data on FAD quantities and positions are not available. The purse seiners reported date, start time, geographic position, and type of set (unassociated set or associated set). The geographic positions of associated sets from drifting natural logs, man-made drifting rafts (drifting FADs), and anchored rafts (anchored FADs) in the period of 1989-1994 and 2005-2013 were used as a proxy for FAD distribution. The total associated set positions in each computational element (1° square at point i, j) in each computational step (month n) are summed (Equation 4.2.1) and used as a proxy for FAD density.

$$\rho_{ijn} \simeq \text{count}(\text{set}_{pqt} | p = i, q = j, t = n) \quad (4.2.1)$$

4.2.2 Model Description

Model Domain

Model domain is 15°S-10°N and 140°E-170°W (Figure 4.4). It mainly covers the overlap of two target areas and includes as many tag release sites as possible for both tagging programs. The Philippines and Indonesia EEZ were excluded because of sparse fisheries data.

Advection-Diffusion Reaction FAD (ADR-FAD) Model

The Advection-Diffusion Reaction (ADR) model estimates the movement and mortality of a fish population using tagging data (*Sibert et al.* 1999). Movement is represented by an advection-diffusion process, which is the equivalent for population in a biased random walk of individual movement (*Okubo and Levin* 2001). The model is based on the number of tagged fish. The number of tagged fish per unit area satisfies the following partial differential equation that shows the local rate of change of tag density (N) at a point (x, y) :

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial N}{\partial x} \right) + \frac{\partial}{\partial y} \left(D \frac{\partial N}{\partial y} \right) - \frac{\partial}{\partial x} (uN) - \frac{\partial}{\partial y} (vN) - ZN \quad (4.2.2)$$

On the right side of equation 4.2.2, the first two terms describe dispersive movements in terms of ‘diffusion’ parameter D . The second two terms characterize directed movement in terms of ‘advection’ parameters u, v that describe east-west and north-south movement, respectively. The last term describes the loss of tagged fish by fishing and natural mortality. Total mortality (Z) is defined by

$$Z_{xyt} = M + \sum_f F_{xyt f} \quad (4.2.3)$$

where $F_{xyt f}$ is the mortality due to fishing by fishing fleet f operating at point (x, y) during time step t and natural mortality M . The natural mortality is assumed be constant at all times and

locations. Fishing mortality is assumed to be a simple function of observed fishing effort

$$F_{xyt f} = q_f \cdot E_{xyt f} \quad (4.2.4)$$

where $E_{xyt f}$ is the observed fishing effort of fleet f operating at point (x, y) during time step t and q_f is a catchability coefficient, which indicates a fleet specific proportionality constant of fish catch by a unit of fishing effort.

The Advection-Diffusion Reaction FAD model (ADR-FAD model) includes two sub-models FAD-Advection and FAD-Diffusion. The FAD-Advection model is based on the simple rule that tuna in a region with lower FAD density move toward a neighboring region with higher FAD density. In the model, the FAD density gradients control the directional movement of tuna along with their ‘natural’ movement in the model. The total advection (u, v) is the algebraic sum of the natural movement (u_r, v_r) and the movement induced by FADs $(\psi \cdot \frac{G_x}{|G|_{max}}$ and $\psi \cdot \frac{G_y}{|G|_{max}})$ where ψ is the FAD attractiveness:

$$\begin{aligned} u &= u_r + \psi \cdot \frac{G_x}{|G|_{max}}, \\ v &= v_r + \psi \cdot \frac{G_y}{|G|_{max}} \end{aligned} \quad (4.2.5)$$

when

$$\begin{aligned} G_x &= \frac{\partial \rho}{\partial x}, \\ G_y &= \frac{\partial \rho}{\partial y} \end{aligned} \quad (4.2.6)$$

where u and v are the east-west and north-south advections (equation 4.2.2). The gradients of FADs in zonal and meridional directions are G_x and G_y , respectively, and the gradients are standardized with $|G|_{max}$. The variable $|G|_{max}$ is the maximum of all absolute FAD gradients over the model domain and duration of a tagging experiment. The advective coefficient parameter is denoted by ψ .

Diffusion in the ADR model is relevant to a random walk in Lagrangian models, which allows

for the dispersal or spread of animals in the model. The diffusion coefficient (D) itself in the traditional ADR model is theoretical and does not consider factors that can influence dispersive movements. In the FAD-Diffusion model, the diffusion component of movement is restricted by the density of FADs. The FAD-Diffusion model assumes that the diffusion decreases exponentially from maximum diffusion (D_{max}) with increasing FAD density (ρ):

$$D = D_{max}e^{-\gamma\rho} \quad (4.2.7)$$

where D_{max} is the maximum of D , and γ is the diffusion reducing rate.

The unit of diffusion here is $nm^2/month$. It can be converted to a more convenient unit by considering the diffusion coefficient to be a circular area over which fish may disperse in one day.

Daily diffusion radius can be estimated by

$$ddr = \sqrt{D_{max}/30 \cdot \pi}. \quad (4.2.8)$$

Closed boundary conditions are used for this study. Fish cannot move out of the boundaries, which means that no fish can move out of the model domain. Hence, at the boundaries

$$\begin{aligned} u &= 0, \\ v &= 0, \end{aligned} \quad (4.2.9)$$

and,

$$\begin{aligned} \frac{\partial N}{\partial x} &= 0, \\ \frac{\partial N}{\partial y} &= 0. \end{aligned} \quad (4.2.10)$$

These conditions ensure that total tagged tuna numbers stay constant in the model domain when fishing and natural mortalities are zero. The initial condition for N is

$$N_{xy0} = \begin{cases} \sum_c \tilde{N}_{x_c y_c 0_c}, & \text{tag release sites,} \\ 0, & \text{elsewhere.} \end{cases} \quad (4.2.11)$$

where $\tilde{N}_{x_c y_c 0_c}$ is the number of tagged fish released at point (x_c, y_c) at time 0 in tag cohort c . A cohort here is defined as total tagged fish released in a one-degree geographic square at time t . Therefore, $\tilde{N}_{x_c y_c t_c}$ is the density of tagged tuna at point (x, y) in the ocean at time t of tag release cohort c . The aggregated density of tagged tuna (N) from all cohorts released up to time t is given by

$$N_{xyt} = \sum_{c=1}^{c_t} \tilde{N}_{x_c y_c t_c}. \quad (4.2.12)$$

4.2.3 Numerical Solution

See Chapter 2

4.2.4 Parameter Estimation

See Chapter 2

4.3 Results

4.3.1 Difference in FAD conditions between RTTP and PTTP

The total number of FAD sets changed between two tagging programs (Figure 4.5). The monthly total fad sets during the RTTP range from 235 to 853 and the mean is 574. During the PTTP, the range is from 127 to 2546 and the mean is 1277. The increase in the number of cells ($1^\circ \times 1^\circ$) with more than one associated set shows the expanding of FAD fishing during the RTTP except for a half year during 1991 (Figure 4.6). The increasing trend continued until the late months of 2009. After the FAD closure was imposed by fishery managers, both the total number of FAD sets and number of cells with FAD rise and wane with the closure periods. In particular, high numbers of FAD sets and expansions of FADs sets were observed before and after every closure.

Accumulated FAD sets during each program were plotted in Figure 4.7. There are differences in the number and distribution between two programs. The number of FADs is much higher and the distribution is wider in the PTTP. In the RTTP, the cells with higher FAD sets are sparsely distributed in the north-west and the east part of the domain, while in the PTTP the cells are accumulated near the land masses.

4.3.2 Comparison in model results

Korean purse seine (KRPS) shows the highest fishing mortality among the fleets in the RTTP, followed by Taiwanese, Japan, and United States purse seines (TWPS, JPPS, and USPS) (Figure 4.8). Fishing mortalities of the two pole and line fleets (JPPL and KIPL) are the lowest. In the PTTP, the Japanese purse seine (JPPS) shows the highest fishing mortality among the nine purse seine fleets. The mortality of the Papua New Guinea purse seine (PGPS) is the second highest, and the rest have similar mortalities. Total fishing mortality (F) is a little higher in the RTTP than in the PTTP, but natural mortality (M) from the PTTP was more than a double that of the RTTP. Consequently, the total mortality (Z) in the PTTP is also double of the RTTP.

The advection resolved into the east-west (u) and the north-south(v) directions. The total advection is determined by the natural movement (u_r, v_r) and the movement induced by both FAD attractiveness (ψ) and FAD gradients (G_x, G_y) (Equation 4.2.5). The natural advective movement parameters are north ($v_r \geq 0$) - east ($u_r \geq 0$) for the RTTP, but south ($v_r \leq 0$) - west ($u_r \leq 0$) for the PTTP (Figure 4.9). The FAD attractiveness, ψ , is about 50 folds higher in the PTTP than the RTTP (Figure 4.9). Because the density distributions of FAD gradients in both the east-west direction (G_x) and the north-south direction (G_y) are very similar (Figure 4.10), the FAD attractiveness (ψ) from two programs are comparable.

The FAD-Diffusion model was plotted by estimated parameters (Table 4.2) from two tagging programs in Figure 4.11. The diffusion reduction rates (γ) from both the RTTP and the PTTP are similar while the maximum diffusion (D_{max}) of the PTTP is 25% smaller than the RTTP. The two plots intersect at the point of nine FADs in 1° squares.

Based on the model results, the displacements exceeded by 50% of tagged fish during their

lifetime (the median lifetime displacements) are computed to compare the travel distances between two programs (Figure 4.12) (*Sibert and Hampton* 2003). In other words, only 50% of the tagged fish moved beyond 491.7 Nmi during the RTTP, and 170.9 Nmi during the PTTP. The median lifetime displacement decreased 65%.

To compare model output to empirical estimates of tuna movement, heading and horizontal displacement of tags from two tagging programs were plotted in Figure 4.13 using a polar plot to identify patterns in tag recaptures. Tags captured east of their release positions had longer displacement than the tags captured from the west in both the RTTP and the PTTP. The fish traveling west increased from 22% in the RTTP to 35% in the PTTP. In the RTTP, 14.7% of tags recaptured were more than 1000 km from the release points. In the PTTP, only 7.2% of the fish were traveled more than 1000 km. Tags from the RTTP were recaptured in a wider range of directions than the tags from the PTTP. The mean travel distance of the RTTP was 461.7km while the PTTP was 344.2km.

4.4 Discussion

Not only did the quantities and densities of associated sets increased dramatically, but the proportion of man-made raft sets also increased between the two tagging programs. The RTTP was initiated in the early 1990s when FADs were just introduced in the WCPO (*Miyake et al.* 2010). The FAD proxy used in this study is associated sets of both natural and man-made rafts. The monthly total FAD sets was lowered during the El Niño years of 1991-2. Lower than normal precipitation during El Niño may reduce natural logs from being available to associated sets. Figure 4.14 shows the total number of associated sets (both logs and FADs sets) and man-made raft associated sets (FAD sets) with time. During the early 1990's, the number of FAD sets is much smaller than the total associated sets. Fluctuations in the total number of associated sets is decoupled from that of FADs sets. Considering both FADs use was in its infancy in the 1990s and the monthly total FAD sets was modulated by ENSO, FAD sets in the RTTP analysis can mostly be attributed to natural log sets. However, when PTTP was initiated in the middle of 2000s, FADs were being extensively and aggressively used in the purse seine fisheries. Total FADs sets and total associated sets followed

the same trend (Figure 4.14). FADs sets account for more than 50% of the total associated sets since 2000. The proportion of FADs sets in the total associated sets may be even higher because FADs are often misidentified as natural logs (*Miyake et al.* 2010).

The effects of FADs on skipjack movements got stronger in the 2000s comparing to the 1990s. Since the 1990s the contribution of the FAD induced movement in advection became significantly higher in the 2000s. However, the diffusion-reducing rate (γ) was similar in both periods. The results imply that the high FAD density affects advective movement more than diffusive movement in skipjack. The difference in the FAD effect on advective movement between two periods could come from: 1) the distributions of two type of FADs (natural logs vs. man-made rafts) are different because of their origins; and 2) the total number of the FADs is important in affecting tuna movement.

It is not possible to determine the effects by each type of FAD here because natural logs and man-made rafts were used undifferentiated in this study. The reason is the way to classify floating objects may have changed over the period since two tagging programs are apart by more than 15 years. Also, misidentification on types of floating objects was often occurred (*Miyake et al.* 2010). However, the large increase in the total number of FADs is indisputable and is likely responsible for shaping tuna movement.

The increase in FAD number induced movement has the effect of increasing the density of FADs and modifying the habitats and movement of tuna (*Marsac et al.* 2000; *Hallier et al.* 2008). FADs could become ‘ecological traps’ for tuna species in a number of ways: 1) the tendency of tuna aggregating of fish to FADs is a strong and quick process; 2) the large number of FADs deployed in the equatorial zone can alter the natural movements of tuna; and 3) FADs negatively affect the growth and natural mortality of tuna associated with FADs. The increase in FAD induced movement from this study supports that the aggregation of fish to FADs had become stronger over time. The decrease in the daily diffusion radius and mean travel distance also lend support to the hypothesis that a large number of FADs could reduce their natural movements. Also, the high reduction in the median lifetime displacement indicates FADs limit skipjack movement. Advective movement in both model output and empirical estimations has been shown that more fish is moving

to the west after the increase in FAD usage. Considering tag release locations of two programs (Figure 4.2, 4.3) are similar, this directional change in their movement should be noted. The higher density of FADs near the land masses (Figure 4.7) may confine the directional movement toward more to the west in the 2000s.

The ever increasing number of FADs begs for an answer on how many FADs within an area would be too many, in which FADs begin to cancel out effects exerted by neighboring FADs on tuna movement. This study calculated a saturation density of nine FADs in 1° squares. When nine FADs are normally distributed in 1° squares, the effective radius of a single FAD is 20 km. The estimated effective radius is higher than but similar to the estimates from other studies: 9-18 km (*Holland* 1990; *Cayré* 1991; *Kleiber and Hampton* 1994; *Girard et al.* 2004). The difference is likely attributed to that previous studies were limited to anchored FADs while this study looks at anchored, drifting, and natural floaters.

Differences among purse seine fishing mortalities in the 2000s decreased from the 1990s except for fleets from Japan, Taiwan, and Korea. The catch of these three countries and Spain accounts for nearly half of the world's purse seine catches (*Miyake et al.* 2010). Significantly higher fishing mortalities for the three countries are observed in the 1990s, but such differences became smaller in the 2000s. This might be due to the vessels of other countries (e.g., the Philippines and Papua New Guinea) being reflagged or entering into joint-ventures with fishery-developed countries (*Miyake et al.* 2010). The catch by developing countries has gradually increased due to reflagged or large joint-venture vessels because these fleets can fish within and outside of the EEZ of the developing countries to which they are now flagged. The estimates of natural mortality (M) in the 2000s are significantly higher than in the 1990s. The reason for higher natural mortality could be due to a couple of different factors. First, it may be caused by discrepancies between reported tag and fishing effort information. Tags are often recaptured from freezers of large commercial purse seiners at unloading. In this situation, the date and location of recovered tags cannot be reported precisely. Incorrect tag information cannot be matched with fishing effort information so these tags cannot be attributed to increased fishing mortality but are instead attributed to natural mortality. Second, higher natural mortality may also be related to the size of tagged fish. The size frequency

distributions of the two programs are similar (20-70 cm), but the distribution of the PTTP skewed toward small fork length (FL) (Figure 4.15). The average FL in the RTTP is about 5cm larger than the PTTP. Because natural mortality is highly size dependent (*Hampton* 2000), the difference is understandable. However, further studies on size dependency are necessary to confirm such differences.

This chapter described the effect of FADs on skipjack movement before and after the expansion of FAD usage. Even though many environmental conditions (e.g., temperature, oxygen, currents, and prey concentration) can influence the movement of tuna, the described changes on their movement between the two periods may indicate strong anthropogenic influences on tuna. Stronger attraction on FADs coincided with the increase in FAD density over last two decades. There are still many gaps in our understanding of how FADs modify the movement of fish, such as how tuna detect FADs and why tuna are attracted to FADs. The dynamics of drifting FADs are still beyond our current knowledge (e.g., the influence of current on the distribution of FADs, the characteristic of fishers' behavior to relocate their FADs). In order to understand what makes FADs attractive to tuna and better manage FADs to assist on stock management goals, collecting FAD information on FAD types and use will be crucial.

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Table 4.1: Estimated reporting rates by nationalities and fishing type for each tagging program taken from the tagging seeding experiments of RTTP (not listed) and PTTP (*Berger et al.* 2014). The first two letters indicate the nationality (flag): Federated State of Micronesia (FM); Korea (KR); Kiribati (KI); Papua New Guinea (PG); Philippines (PH); Solomon Islands (SB); Taiwan (TW); United States of America (US); Vanuatu (VU); and Japan (JP). The second two letters indicate the fishing types: purse seine (PS) and pole and line (PL).

RTTP		PTTP	
fleet	reporting rate	fleet	reporting rate
SBPL	0.72	SBPS	0.98
SBPS	0.64	PHPS	0.80
KIPL	0.62	PGPS	0.81
USPS	0.59	VUPS	0.69
PHPS	0.58	TWPS	0.65
JPPS	0.42	USPS	0.60
JPPL	0.3	KRPS	0.40
TWPS	0.06	JPPS	0.23
KRPS	0.02	FMPS	0.32

Table 4.2: Estimated parameters from two tagging programs.

	RTTP		PTTP	
	estimation	std	estimation	std
ddr	15.3	0.23	13.3	0.19
D_{max}	20398	661.9	15501	485.4
γ	0.14	0.028	0.11	0.014

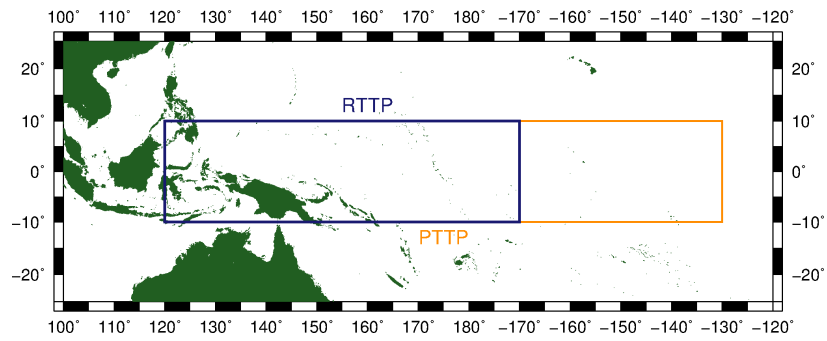


Figure 4.1: The target areas of the RTTP in blue and PTPP in orange.

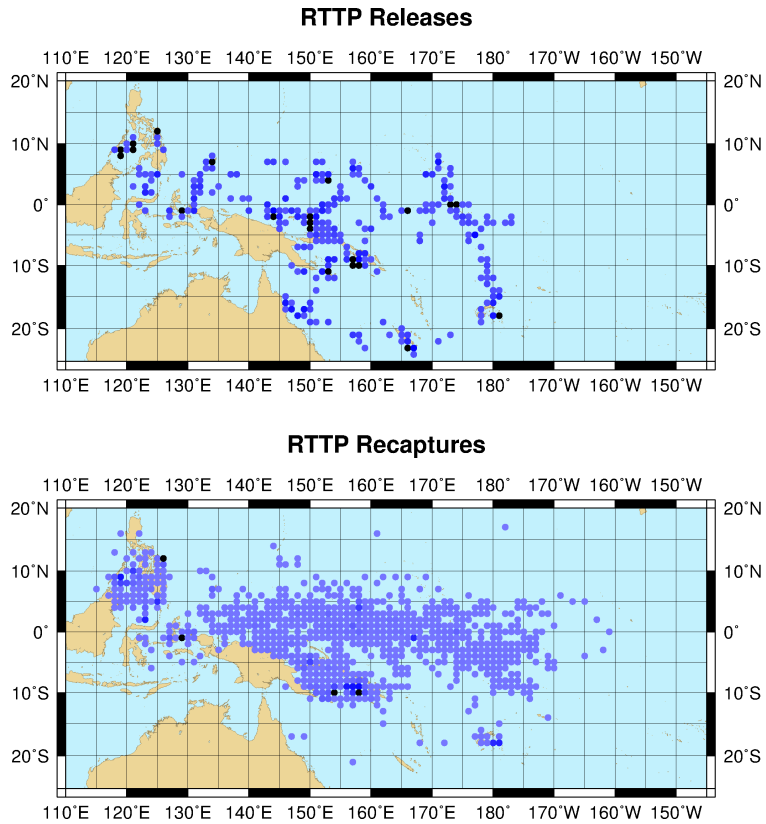


Figure 4.2: Maps of the WCPO with skipjack tag releases and recaptures during RTTP.

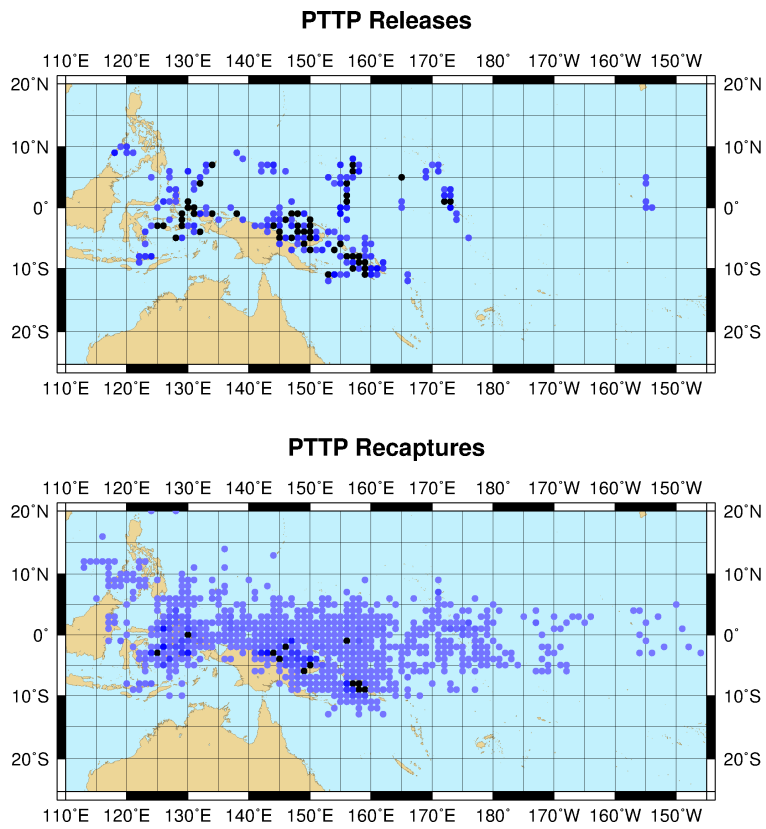


Figure 4.3: Maps of the WCPO with skipjack tag releases and recaptures during the first seven years of PTTP.

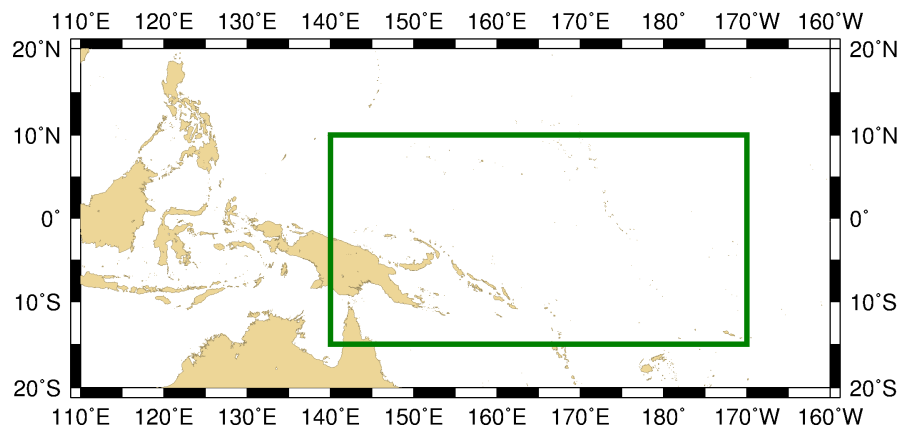


Figure 4.4: Model domain for the RTTP and the PTPP.

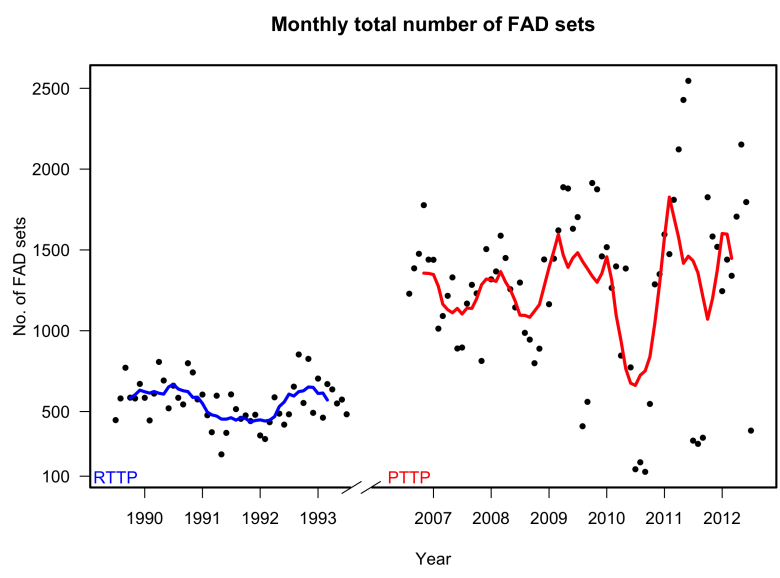


Figure 4.5: Monthly total number of FAD sets (dots) and 4-month moving average (lines) during the RTTP and the PTTP.

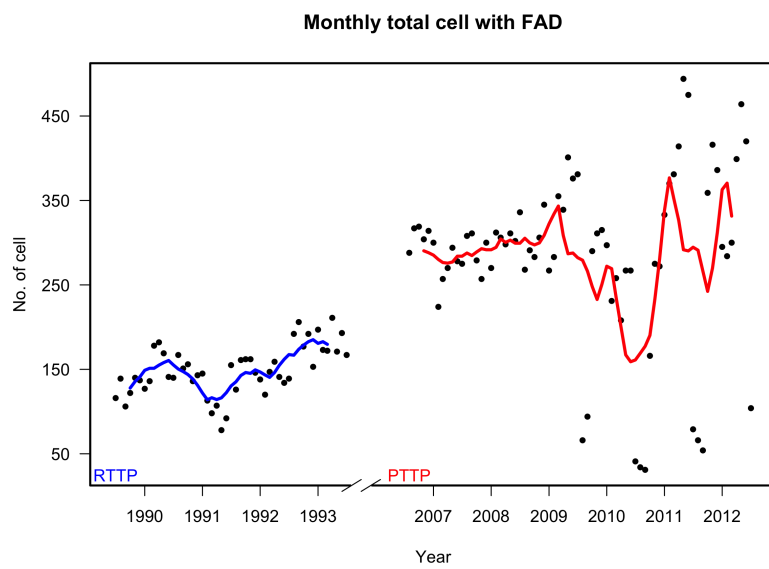
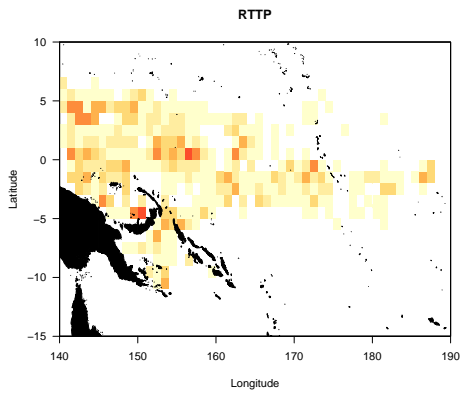
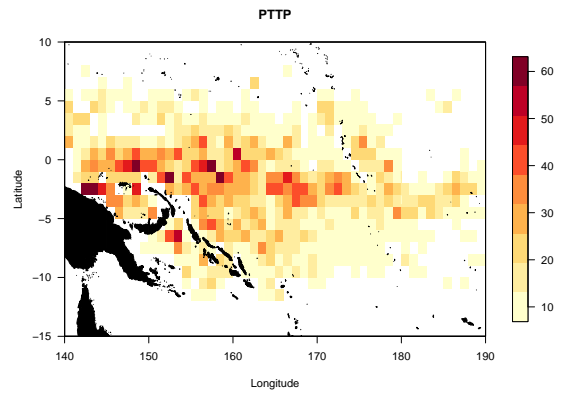


Figure 4.6: Monthly total number of cells with more than one associated set (dots) and 4-month moving average (lines) during the RTTP and the PTTP.

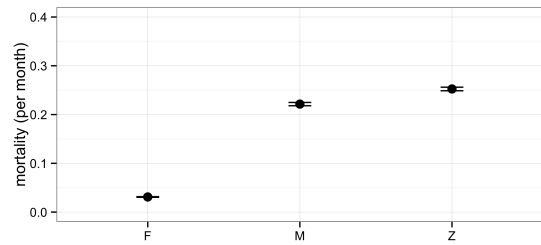
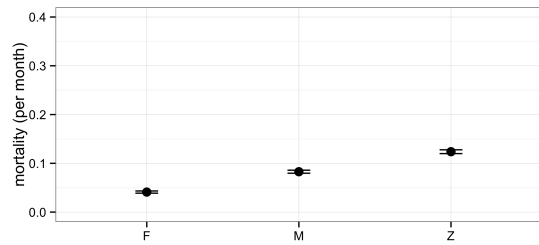
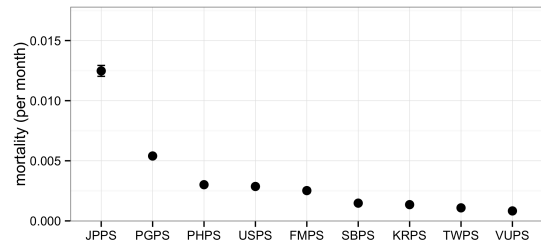
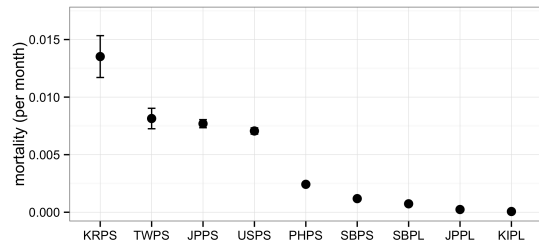


(a) RTTP (1989-1992)



(b) PTTP (2006-2013)

Figure 4.7: Accumulated FAD sets during the programs: (a) RTTP and (b) PTTP.



(a) RTTP

(b) PTTP

Figure 4.8: Estimated parameters from the RTTP and the PTTP skipjack data. Estimated fishing mortality by fleet, total fishing mortality (F), natural mortality (M), total mortality (Z) over the model domain in two tagging periods. The error bars are 2 standard deviation.

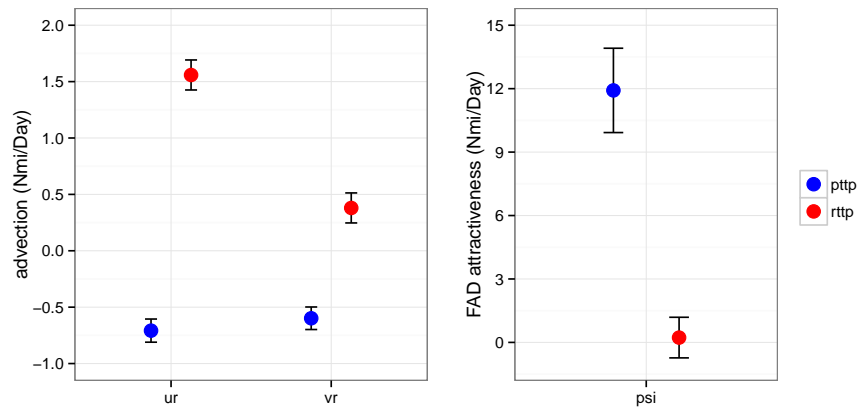
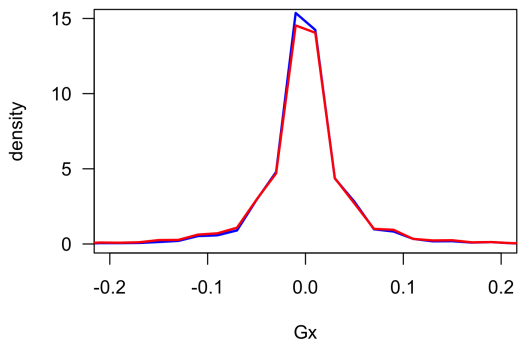
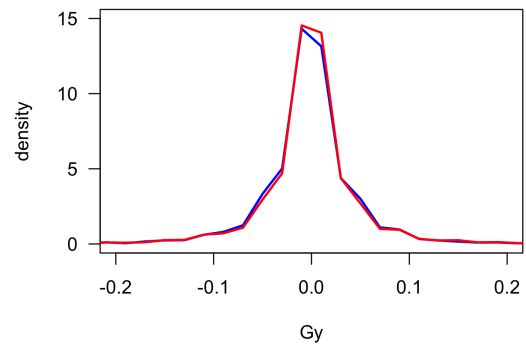


Figure 4.9: Estimated natural movement (u_r, v_r) and FAD attractiveness (ψ) from the RTTP and PTPP. The error bars are two standard deviations.



(a) G_x



(b) G_y

Figure 4.10: Density distribution of FAD gradients in east-west direction (G_x) and north-south direction (G_y) from the RTTP (blue) and the PTPP (red).

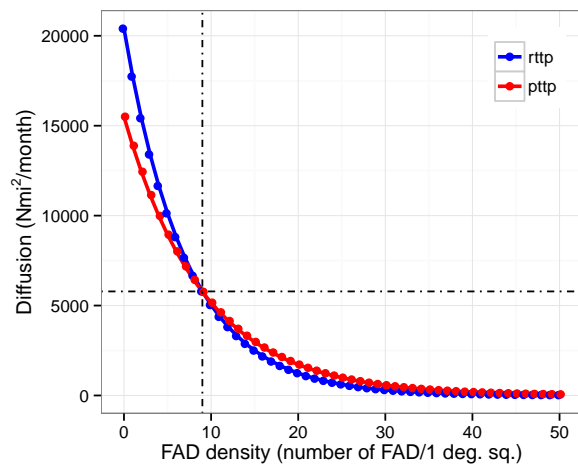


Figure 4.11: FAD-diffusion model plots by estimated parameters from the RTTP (blue) and the PTPP (red). The dashed lines indicate the intersection of two lines at nine FADs in 1° squares.

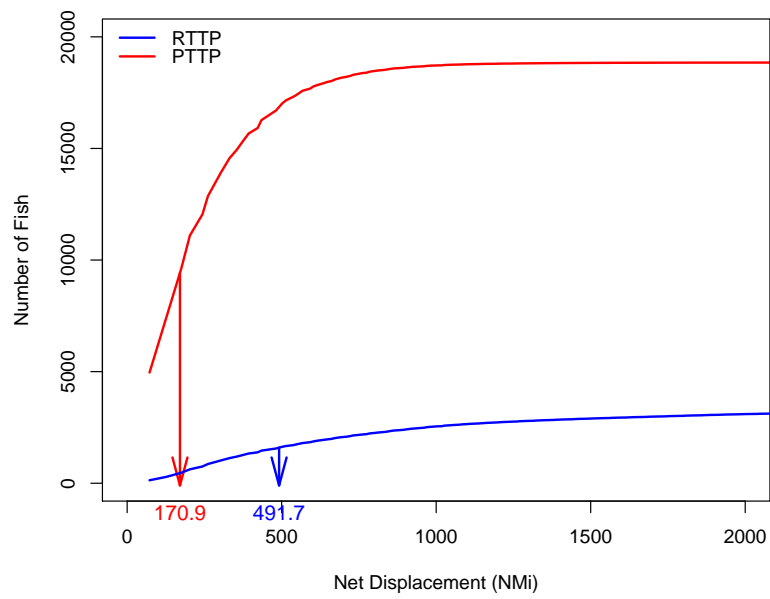
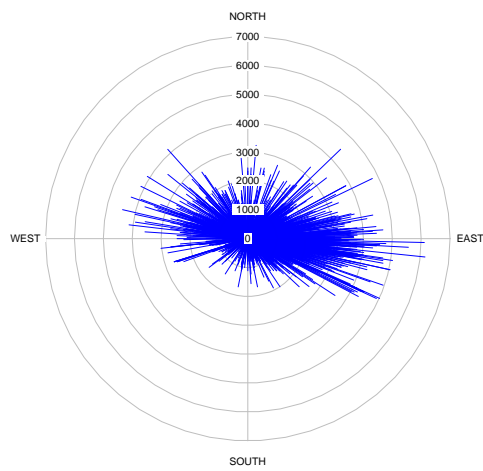
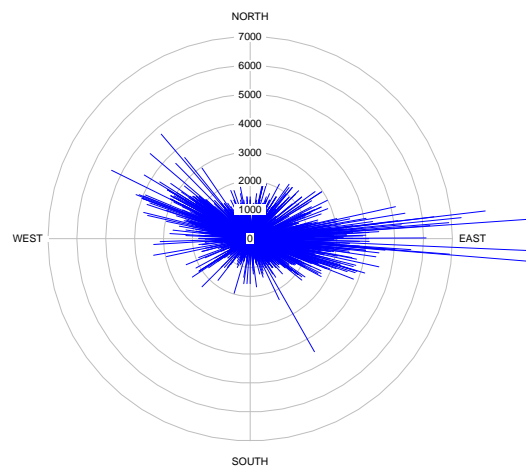


Figure 4.12: Median lifetime displacements of the RTTP and the PTTP.



(a) RT1990 (n=9958)



(b) PT2000 (n=22769)

Figure 4.13: Heading and horizontal displacement of tags in polar plots from two tagging programs. Each line indicates heading and horizontal displacement of a tags. The numbers are distances from the center in km.

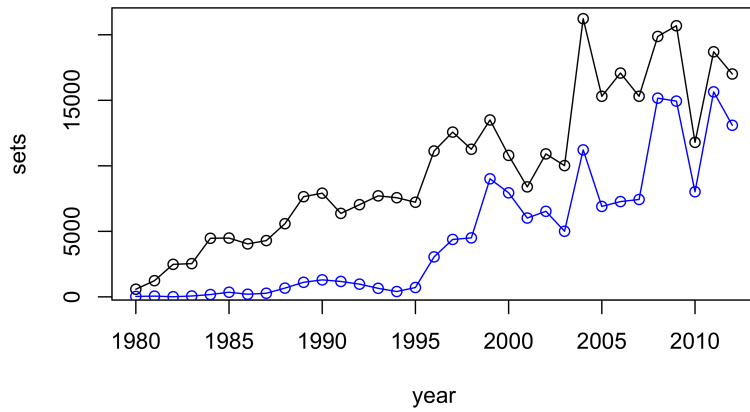


Figure 4.14: The number of total associated sets (black) and FAD sets (blue) from 1980 to 2012.

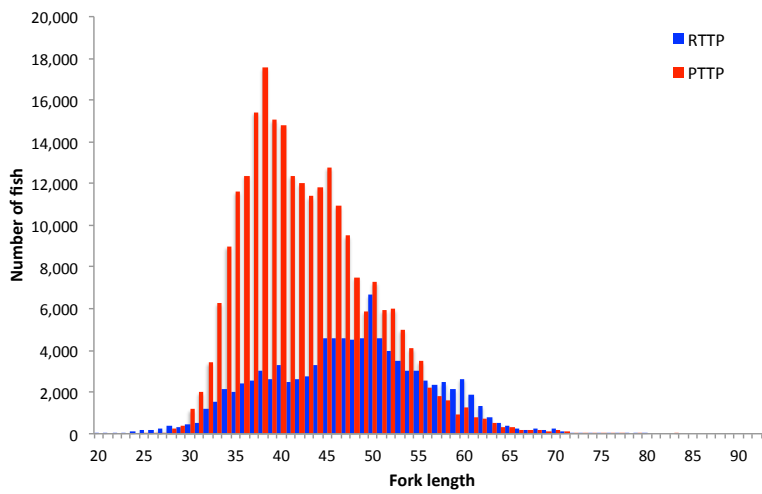


Figure 4.15: Size-frequency distributions of skipjack released during the RTTP (in blue) and the PTTP (in red). The x-axis denotes fork length (FL, in cm) and the y-axis denotes the number of fish released. The average FL in the RTTP is 47.6cm and in the PTTP is 42.7cm.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Research Synthesis

The specific goals of this dissertation are: 1) to develop a movement model that can quantify the influence of FADs on tuna movement; 2) to determine the influence of FADs using the model; and 3) to compare the effects using regional and density scales. The effect of FADs on the skipjack movement became stronger with the increase in FAD density over the past two decades. The effectiveness of FADs on skipjack movement differed between the open ocean and the coastal area.

In Chapter 2, the Advection-Diffusion Reaction-FAD model (ADR-FAD model) was described and simulated using commercial fishing effort data and conventional tagging data. Fish movement in the ADR-FAD model is controlled by the attractive and hindering tendency of FADs. In the model, two assumptions were hypothesized: 1) the directional movement of fish is attracted to areas with higher FAD gradients; and 2) the diffusive movement of fish is reduced with higher FAD density. Accurate input data is essential to obtain realistic results from the modeling work, however, currently available data are largely limiting. Even though the distribution of FADs is essential to run the model, accurate and detailed FAD information is not available. Most FADs used in commercial fisheries are attached to tracking devices that allow fishers, who share and operate them, to monitor them. However, such data are kept confidential as they are of particular commercial importance to competing fishers. The only reported information on FADs is the fishing sets made from FADs that, at best, provide partial information on where and how FADs are used. Such fisheries data include some gaps that are both intentional and unintentional. For example, fisheries data in some parts of the study area are not available due to the lack of information infrastructure or their remote locations. Moreover, some fisheries data are often reported with time lags. These data inadequacies were explored in the Chapter 2 to qualify their potential impacts and find possible remedies. The accuracy of the ADR-FAD model was also accessed with simulation

efforts. To this end, more than 10,000 simulations were computed to test the model, which took over 1,600 computational hours. Overall, the ADR-FAD model works better when the model domain is set to exclude data poor areas and when data of questionable quality were excluded.

In Chapter 3, the movement of skipjack tuna was estimated using the ADR and ADR-FAD models which use an extensive database of conventional tag data. The purposes of this chapter were: 1) to select the better model of the two by comparing the results of both models; 2) to compare the influence of FADs in open and coastal ocean. Results from the two models were very similar, but the ADR-FAD model fit the data a little better than the ADR model. Estimations of the mortality parameters from both models were very similar. Because both models utilized the same fishing effort data, the FAD data used in the ADR-FAD model is only a subset of the fisheries data. Such a limitation may account for the similar model results. Nonetheless, this study shows that the influence of FADs on the skipjack movement was stronger in the open ocean than the coastal ocean. Because most of the FADs in open ocean are drifting FADs and most of FAD in coastal ocean are anchored FADs, the differences in FAD types may suggest differing behavior processes driving the association of tuna with drifting and anchored FADs. Considering the FAD distribution data used in the model is the minimum density, the influence of FADs on skipjack movement may be bigger than the model results. As a result, including FAD information into the ADR model can improve the estimation of the skipjack data. The ADR-FAD model showed better results when the model domain was divided into two regions. The results supported the varying effects of FAD in the open and coastal ocean.

The use of FADs in the WCPO has increased dramatically in last 20 years and, consequently, the catch from FAD sets increased as well. These trends were captured by the two sets of tagging data, collected at different time points during the rapid increase in FADs: the Regional Tuna Tagging Project (RTTP, 1989-1992) and the Pacific Tuna Tagging Programme (PTTP, 2006-Present). In Chapter 4, the influence of FADs on skipjack movement during two periods was estimated using the ADR-FAD model. Results were compared to test the hypothesis that skipjack movement increased

when FAD density increased. The average density of FAD sets during the PTTP is about a triple of that in the RTTP. The FAD induced movement is significantly higher in the PTTP than the RTTP. However, the diffusion-reducing rate of FADs was similar in both periods. The traveling distance of tagged fish was lower in the PTTP than in the RTTP; the direction pattern of fish during the PTTP was more to the west, moving closer to the land mass. These results suggest that higher FAD density affects advective more than diffusive movement in skipjack. This lends support to the hypothesis that FADs modify the habitats and movement of tuna by the increasing the density of floating objects (*Marsac et al.* 2000; *Hall* 1998). Even though many environmental conditions can influence the movement of tuna, the main finding of this chapter is that the expansion of FAD usage may present a strong anthropogenic influence on tuna movement.

5.2 Future Research and Implication

A major finding of this dissertation is that the total number of FADs strongly affects tuna movement. Stronger attraction on FADs paralleled the increase in FAD density over last 20 years. Limiting the number of FADs may be unavoidable in order to tackle the problems associated with FAD set fishing.

The current biggest problem is the high catch on juvenile bigeye tuna. Catch from FAD-associated schools have much higher proportion of juvenile yellowfin and bigeye tuna compared to catch from free schools. High catches of juveniles reduce the yield per recruit of each cohort recruited in the fisheries. The impact of the catch on juvenile bigeye tuna is much more serious than it is on yellowfin tuna since the stock size of bigeye tuna is much smaller than yellowfin tuna (*Aires-da Silva and Maunder* 2012). To reduce the high mortality of juvenile bigeye tuna, two Pacific tuna regional fisheries management organizations, the Western and Central Pacific Fisheries Commission (WCPFC) and Inter-America Tropical Tuna Commission (IATTC), apply time-area closures. In the Eastern Pacific, all purse seine fisheries are closed in the convention area for three months, and a part of the convention area is closed for all types of fishing for one month (*IATTC* 2013). In the Western and Central Pacific, the WCPFC has a three-month ban on FADs in their convention area (*Anonymous* 2014). However, the efficiency of the time-area closures for reducing

fishing mortality on juvenile bigeye is questionable (*Fonteneau and Chassot 2014*), as fishing effort redistributes outside closed area; and effort increases before and after closures (*Harley and Suter 2007; Torres-Irineo et al. 2011*). An increase in fishing effort before and after closures was also observed in this study (Chapter 4). Fishing effort and, subsequently, fishing mortality on juvenile bigeye tuna could be reduced when the number of FADs is controlled. This study shows that stronger attraction to FADs corresponded to the increase in FAD density over time, and therefore setting a limitation on the number of FADs may offer more direct impacts on reducing fishing mortality.

Limiting the number of FADs would also reduce other ecological impacts from FAD fishing such as catch on non-target species. Even though the rate of bycatch by purse seine is lower than other tuna fishing methods, the rate of bycatch from FAD-associated catch is higher than from free-school catch (*Dagorn et al. 2013*). The bycatch often includes vulnerable species such as turtles and sharks. In particular, silky sharks (*Carcharhinus falciformis*) and white tip sharks (*Carcharhinus longimanus*) are highly exploited by FAD sets fishing. These species are the least resilient from high exploitation because of their slow growth, late maturation, and long reproductive cycle (*Musick et al. 2000*).

To set a limit on FAD number, accurate information on FADs is needed. Currently, the use of FADs is not monitored by any tuna regional fisheries management organization. One of the difficulties of this study was the availability of FAD data. Unlike anchored FADs (aFADs), drifting FADs (dFADs) are hard to monitor because they are drifting around with the ocean currents. However, recent dFAD technology has allowed fishers to monitor not only dFAD locations but also fish biomass underneath the dFADs. Collecting all data on FAD use may not be practical but, at a minimum, the number of dFADs aggregated as a daily or monthly average number of active dFADs deployed by each fleet should be reported.

Such FAD data would provide a measure of FAD fishing pressure and could be used to evaluate the average density of FADs. The data also can improve how fishing effort is accounted for the purse seine fisheries. Currently, the effort units of purse seine fisheries are defined as fishing and/or searching days or numbers of fishing sets. Fishers actively monitor the fish biomass under their

dFADs to decide where to fish and when to se, but this behavior is not reflected in the fishing effort. Not reflecting this behavior in the measure of fishing effort may cause higher catch per unit effort (CPUE) of FAD sets than free-school sets. The monitoring activity on dFADs should be quantified to reflect fishing effort.

Using underestimated fishing effort on monitoring FADs may affect on stock assessments. To date, skipjack in the Pacific has been evaluated that their stock is stable (*Rice et al. 2014*), but, the change in fishing effort caused by FADs has not yet been considered by any stock assessment. Uncertainties introduced by an underestimated fishing effort on stock assessment should be investigated. Adopting the proposed data collection on the numbers of active dFADs should be a start.

Continued fishing on dFADs may negatively affect on skipjack stock status by reducing their spawning potential (*Fonteneau and Chassot 2014*). The suggestion is based on the observation that skipjack do not store fat that allow them to spawn (*Grande 2013*). The movement of dFAD sets does not correspond with convergence fronts that are likely areas for foraging (*Wang et al. 2014*). It implies that associated schools with dFADs may encounter less prey, comparing to free-schools that aggregate at convergence fronts. A large percentage of fish with empty stomachs and poor conditions of associated schools support the idea (*Hallier et al. 2008; Robert et al. 2014*). Effects on spawning conditions caused by dFADs could be investigated by extending the ADR-FAD model by incorporating prey distributions from a model such as SEAPODYM (*Lehodey et al. 2008*). In such a model, spatial dynamics of tuna are forced by the a bio-physical environments and FADs, and spawning habitat can define by prey and temperature.

Fisheries innovations often can improve our efficiency in fishing and open new ways to capture large biomass of fish from the ocean. We saw the major innovation in tuna fisheries for the last two decades by introducing dFADs. They will continue to make a huge impact in the future if we keep using them. Without information on the number and usage of dFADs, their impacts on changing tuna populations need to be identified as soon as possible. With results from the ADR-FAD model, this study supports to FADs as another powerful anthropogenic force, along with greenhouse gas emissions in forcing changes in marine ecosystems and economically important fisheries. Adequate

data reporting and effective control management measures on FAD usage will be key to sustainable fisheries in the decades to come.

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