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Exchange rates of yellowfin and bigeye tunas and fishery interaction between Cross seamount and near-shore FADs in Hawaii

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Abstract − Yellowfin and bigeye tunas (*Thunnus albacores* and *Thunnus obesus*) were tagged and released between August 1995 and December 1997 at Cross Seamount and NOAA weather buoys about 200 Nmi south of Honolulu. The release and recapture data were stratified into five sites, and a bulk transfer model was used to estimate natural mortality, fishing mortality and transfer rates between the five sites. Bigeye are much more persistent at Cross seamount and less vulnerable to the fishery than yellowfin. Fishing accounts for about 5 % of the total mortality of both bigeye and yellowfin at Cross Seamount. Yellowfin are a major component of catches at inshore FADs in Hawaii. The rate of immigration from Cross Seamount to the inshore FADs is very low for both species. The fishing mortality at Cross seamount is substantial but is not adversely impacting the populations either at Cross or the inshore FADs. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

tagging / tuna fish / seamount / fishery / model / FAD / *Thunnus albacores* / *Thunnus obesus*

Résumé − Taux d'échanges d'albacores et de thons obèses et interaction sur la pêche entre le mont sous-marin « Cross » et les dispositifs de concentration de poissons à Hawaï. Des albacores et des thons obèses (*Thunnus albacores* et *Thunnus obesus*) ont été marqués et relâchés entre août 1995 et décembre 1997 au mont sous-marin Cross et aux bouées météorologiques de la NOAA à environ 200 milles nautiques au sud d'Honolulu. Les données de marquage et de recapture stratifiées en 5 sites et un modèle de transfert global a été utilisé pour estimer la mortalité naturelle, la mortalité par pêche et le taux de transfert entre les 5 sites. Le thon obèse demeure davantage au mont sous-marin Cross, et est moins vulnérable à la pêche, que l'albacore. La pêche au niveau du mont sous-marin Cross, compte pour environ 5 % de la mortalité totale pour les deux espèces. L'albacore est une composante majeure des captures au niveau des dispositifs de concentrations de poissons (DCP) à Hawaï. Le taux d'immigration du mont sous-marin Cross, vers les DCP côtiers, est très faible pour les deux espèces. La mortalité par pêche au niveau du mont sous-marin est conséquente mais n'a pas d'impact défavorable sur les populations, que ce soit au mont sous-marin Cross ou au niveau des DCP côtiers. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

marquage / thon / mont sous-marin / pêche / *Thunnus albacores* / *Thunnus obesus*

1. INTRODUCTION

Recent tuna tagging projects in Hawaii have tagged and released yellowfin and bigeye tuna since 1995. During the period August 1995 – December 1997, tagging activity was confined to the Cross Seamount and NOAA weather buoys south of the island of Hawaii. Previous analysis of the data from this period clearly showed that the gross attrition rate of tagged yellowfin from the Cross Seamount aggregation was much greater than that of bigeye, but that the global loss rates of both species from the entire recapture area were equal (Holland et al., 1999). The purpose of the work described in this paper is to attempt to partition the gross attrition rates for these two species into components due to fishing mortality, movement to other sites, and "natural" mortality. We will develop a series of models of increasing complexity to describe

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Table I. Summary of tag releases and recaptures by site and species used in this analysis.

Site	Bigeye	Yellowfin	Total
	Releases		
Cross Seamount	1928	867	2795
Buoy 2	790	323	1113
Buoys 3 & 4	627	183	810
Inshore FADs	0	0	0
Other	55	86	141
Total	**3400**	**1459**	**4859**
	Recaptures		
Cross Seamount	96	92	188
Buoy 2	76	12	88
Buoys 3 & 4	8	6	14
Inshore FADs	7	10	17
Other	7	7	14
Total	**194**	**127**	**321**

the tag recapture process and apply recently developed approaches and tools for statistical modeling to estimate the model parameters. Finally we will apply the results to issues of interest to fishery managers.

2. MATERIAL AND METHODS

This analysis is restricted to recaptures of tagged bigeye and yellowfin released between August 1, 1995 and December 31, 1997. The recapture period is restricted to the period prior to December 31, 1998. These restrictions allow the use of simplified models. The number of recapture sites is relatively low so that there is no need to resort to models with high spatial resolution (Sibert et al., 1999), and there are few recaptures of large fish that would require introduction of age-dependent processes. A total of 4 859 tag releases and 321 recaptures were used in this analysis as shown in *table I*. Fishing effort data were obtained from the State of Hawaii Division of Aquatic Resources (HDAR). All data were aggregated into five sites and 10-day time periods. This stratification produced 33 tag release cohorts for bigeye and 29 cohorts for yellowfin. The observed exchanges are presented in *figure 1*. The selection of sites is relatively arbitrary; these sites were chosen so that the number of tagged fish of both species recaptured at each site was greater than 10 (*table I*). See Itano and Holland (2000) for descriptions of the fishery, fishing grounds and details of the tagging program.

The models used to analyze the Cross Seamount tagging data are derived from simple tag attrition models. Tag attrition models are widely used (Kleiber et al., 1987) and typically consist of components that describe the dynamics of the tagged population, the recapture of tagged fish by the fishery, and the reporting of recaptured tags. The basic tag attrition model

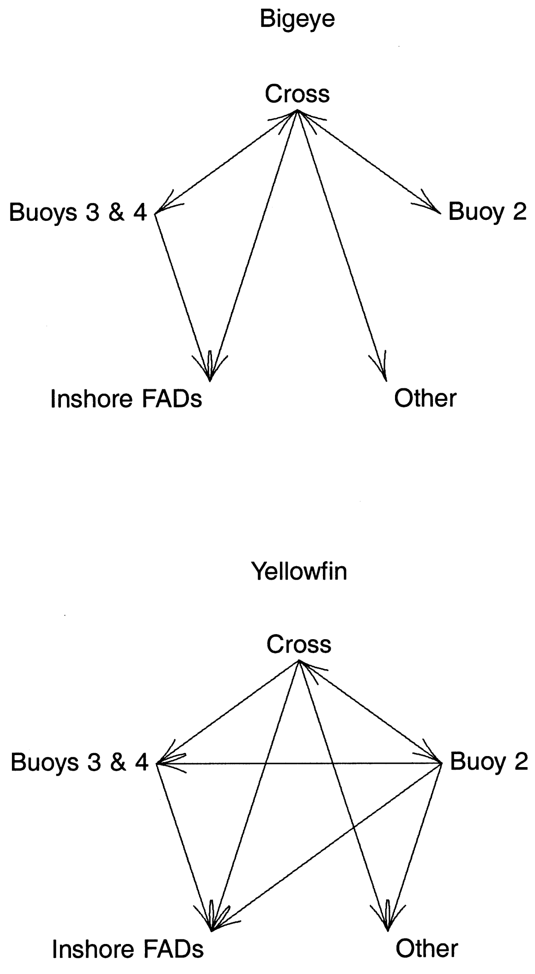

Figure 1. Observed transfers of bigeye and yellowfin between recapture sites. Arrows that point in both directions indicate that transfers were observed in both directions. Lack of arrows indicates that no transfers were observed.

simply describes the rate of loss of tagged fish from the population:

$$\frac{dN_s}{dt} = -Z_s N_s \qquad N_s = N_{s0} \qquad \text{at } t = 0$$

$$\frac{dC_s}{dt} \propto N_s \qquad C_s = 0 \qquad \text{at } t = 0 \tag{1}$$

where N_s is the number of individuals remaining in a cohort of tagged fish of species s, N_{s0} is the number of tagged fish released, t is the time that the tags have been at liberty, Z_s is the gross attrition rate, C_s is the cumulative number of tags returned, and the subscript s (s = 1,2) indicates that the attrition rate may vary between species of fish. This model describes a simple exponential decay of the tagged population and is the basis for the analysis by Holland et al. (1999) to conclude that bigeye and yellowfin differ in their fidelity to Cross Seamount, i.e. that Z does indeed vary between species of fish. Under circumstances where auxiliary information from the fishery is available, the total attrition rate can be partitioned into components due to natural mortality and fishing mortality. For example :

$$\frac{\mathrm{d}N_s}{\mathrm{d}t} = -\,(M_s + f_s)\,N_s \qquad N_s = N_{s0} \text{ at t} = 0$$
$$\frac{\mathrm{d}C_s}{\mathrm{d}t} = \mathrm{f}_s\,\mathrm{N}_s \qquad \mathrm{C}_s = 0 \text{ at t} = 0 \;\; \mathrm{f}_s = \mathrm{q}_s\,\mathrm{E} \tag{2}$$

where f_s is the fishing mortality rate on species s, q_s is a coefficient of proportionality between fishing mortality for species s and fishing effort (the “catchability” coefficient), and E is some measure of fishing effort. These equations predict the expected number of tag recaptures, and the model parameters can be estimated by fitting the model to the observed number of recaptures. This analysis assumes that all recaptured tags are reported to the tagging program. The reporting rate is often considered to be a function of how well fishers co-operate with the tagging program. Staff of the Hawaii Tuna Tagging Program made a major commitment of time and effort to promote good relations with the fishing community and are confident that nearly all tags recaptured by Hawaii-based fishing fleets are reported.

If recapture sites are known, components of attrition due to movement between sites can also be estimated, further partitioning total attrition into its components. Details of tag attrition models increase as the number of recapture sites, number of species and number of tag cohorts increase. Nevertheless, the basic ideas and model structure remain unchanged, and the strategy of partitioning total attrition into its components can still be applied. The model used in this analysis is written :

$$\frac{\mathrm{d}N_{ski}}{\mathrm{d}t} = -\left(M_s + f_{si} + \sum_j T_{sij}\right) N_{ski} + \sum_j T_{sji}\,N_{skj}$$
$$\frac{\mathrm{d}C_{ski}}{\mathrm{d}t} = f_{si}\,N_{ski}$$
$$f_{si} = q_{si}\,\tilde{E}_i \tag{3}$$

where the subscripts i and j (i, j = 1,2,...,5) indicate release and recapture sites. Movement between sites is expressed by the transfer coefficients, T_{sij}, rates of transfer of species s from site i to site j ($T_{sii} = 0$). $\tilde{E}_i$ is the normalized fishing effort as defined below. All components of attrition may be species-specific and some components may also be site-specific. The subscript k indicates that the equation applies to the tag release group k.

Self-reported data from fisheries are often problematical. The HDAR data used in this analysis has sufficient information to compute an estimate of fishing effort as boat-days fished in any arbitrary time stratum, but the relationship between catch and fishing effort appears to be highly variable between sites and the two species. Also, there are consistent differences in fishing methods between inshore and offshore sites such that units of fishing effort at different sites are not comparable. The fishing effort was normalized to the mean fishing effort for the entire recapture period:

$$\tilde{E}_{it} = \frac{E_{it}}{\bar{E}_i} \tag{4}$$

where E_{it} is the observed fishing effort at site i during time period t, $\bar{E}_i$ is the fishing effort at site i averaged over all time periods. Some time × area strata for which tags were returned lack fishing effort data. The fishing effort for these strata was assigned a value of 1, the mean of the normalized fishing effort for every site. Normalization reduces the variance of the fishing effort and rescales the catchability coefficients to be equal to the mean instantaneous fishing mortality rate.

The relationship between fishing effort and catch is notoriously variable. There is little reason to believe that the catchability coefficient is constant over time and place, i.e. q is likely to vary between seasons and between recapture sites. Fournier et al. (1999) introduced the concept of “effort deviations” to model the variability in the effort – catch relationship. Applying this concept, the fishing mortality in equation (3) can be rewritten as :

$$f_{sit} = q_{si}\,\tilde{E}_{it}\,e^{\varepsilon_t} \tag{5}$$

where ε_t are normally distributed random variables with mean zero and variance σ_ε^2 representing transient deviations in the effort – fishing mortality relationship within each time period t. Since this variability translates to catch through equation (3), ε also captures variability in the effort – catch relationship.

A semi-implicit finite difference approximation was used to obtain numerical solutions to equations (3). Model parameters were estimated by maximum likelihood using a Poisson likelihood function. The parameter estimates are the numerical values of q, T and M which maximize :

$$ln\,L = ln\,\mathrm{P}(\,q, T, M, \varepsilon \,|\, C_{skit}, E_{it}\,) =$$
$$ln \prod_{skit} \left[\frac{\hat{C}_{skit}^{\,C_{skit}}\, e^{-\,\hat{C}_{skit}}}{C_{skit}\,!} \right] - \mathrm{w}_\varepsilon \sum_t \varepsilon_t^2 \tag{6}$$

where $\hat{C}_{skit}$ is the predicted number of tag returns from the solution of equations (3) and C_{skit} is the observed number of tag returns. The maximum was determined by minimizing – ln L using the ADModel Builder non-linear optimization package (Otter Research Ltd., 1994).

w_ε is a constant reflecting assumptions about the variance of the effort – catch relationship. In this analysis, $w_\varepsilon = 1$, a value allowing σ_ε^2 to be approximately 10 % of the total likelihood. In other words we assume that 10 % of the variability in the tag recap-

Table II. Likelihood-ratio tests for increasing model complexity; *n* indicates the number of estimated parameters, partitioned into the number of parameters per model component, *M*, *q*, *T*, and ε; χ^2 is the likelihood ratio; *df* is the increase in number of parameters over the previous model; *P* is the significance level of the $\chi^2(df)$ test*.

Model	*n*	ln *L*	Compared To	χ^2	*df*	*P*
$M_1Q_1T_1$	1,5,10,0	–535.170				
$M_2Q_1T_1$	2,5,10,0	–535.082	$M_1Q_1T_1$	0.176	1	0.325
$M_1Q_2T_1$	1,10,10,0	–518.535	$M_1Q_1T_1$	33.270	5	> 0.999
$M_2Q_2T_1$	2,10,10,0	–516.885	$M_1Q_2T_1$	3.3	1	0.931
$M_2Q_2T_2$	2,10,20,0	–509.493	$M_2Q_2T_1$	14.784	10	0.860
Effort Deviations Included						
$M_1Q_1T_1$	1,5,10,102	–391.618				
$M_2Q_1T_1$	2,5,10,102	–391.612	$M_1Q_1T_1$	0.012	1	0.087
$M_1Q_2T_1$	1,10,10,102	–376.551	$M_1Q_1T_1$	30.134	5	> 0.999
$M_2Q_2T_1$	2,10,10,102	–374.163	$M_1Q_2T_1$	4.776	1	0.971
$M_2Q_2T_2$	2,10,20,102	–356.172	$M_2Q_2T_1$	35.982	10	> 0.999
$M_2Q_2T_2$	2,10,20,102	–356.172	$M_2Q_2T_2$	306.642	102	> 0.999

* The sequence of numbers indicating the number of estimated parameters refers to the number of parameters associated with M, Q and T respectively. The final number is the number of effort deviations estimated. The total number of estimated parameters is the sum of the sequence.

tures is due to variability in the effort – catch relationship and 90 % is due to the variability in tag population dynamics. Large values of w_ε force σ_ε^2 to be near zero, and the effort deviations have no effect on the parameter estimates. Small values of w_ε allow the values of ε^2 to be as large as necessary to produce exact agreement between predicted and observed recaptures.

3. RESULTS

A system with 5 sites has a total of 20 possible transfers, but only 10 exchanges were actually observed for both species combined (*figure 1*). Therefore, only those 10 transfer coefficients were estimated for which exchanges of either bigeye or yellowfin were recorded; all other transfer coefficients were assumed to equal zero. The model represented by equations (3) allows for all attrition components (*M*, *q*, and *T*) to be species specific, but it is not an absolute requirement. Our strategy is to start with the simplest model, one in which all attrition components are the same for both species, to add species-specific parameters in a stepwise fashion, and to test for improvement in fit of the model to the data at each step using the value of the likelihood function, equation (6), as a measure of goodness of fit. The effects of increasing model complexity are presented in *table II*. Each model is identified by a code indicating which parameters are species-specific, e.g. M_1 indicates a model in which a single value of natural mortality (*M*) is estimated for both species, and M_2 indicates a model in which two values of *M* are estimated, one for each species. Agreement between model prediction and observation is indicated by the value of the log likelihood function, the larger the value of ln *L*, the closer agreement. The significance of the improvement in fit is evaluated with a likelihood ratio test (Brownlee, 1965) using a significance level of $P > 0.9$. Significance tests are confined to tests of adding species-specific parameters to a single attrition component, i.e. models are considered to be “nested” only *within* attrition components. The simplest model is $M_1Q_1T_1$, both species have identical attrition rates, with 16 estimated parameters (one value of *M*, five values of *q*, and ten values of *T*). The agreement is improved slightly by adding species-specific natural mortality ($M_2Q_1T_1$), but the improvement is not statistically significant ($P < 0.9$). The addition of species-specific catchability ($M_2Q_2T_2$) does improve the fit significantly ($P > 0.999$) and the $M_2Q_2T_1$ model is a slight further improvement. Inclusion of specific-specific transfer coefficients, $M_2Q_2T_2$ model, improves agreement between observed and predicted tag returns, but the improvement over the $M_2Q_2T_1$ model is not significant ($P < 0.9$).

The second part of *table II* repeats the model-selection process for models which include variability in the relationship between catch and effort. The results are generally similar, but the levels of significance are higher and the $M_2Q_2T_2$ model fits the data significantly better than the $M_2Q_2T_1$ model. The last line in *table II* evaluates the effect of including effort deviations in the $M_2Q_2T_2$ model. When this source of variability is included, the fully species-specific model, $M_2Q_2T_2$ provides the best agreement between observed and predicted tag returns for both species.

This model predicts both the location and time of tag recaptures. *Table III* shows the numbers of observed and predicted recaptures tabulated by release site, recapture site and species. In general, the agreement between observed and predicted tags is excellent, particularly at Cross Seamount and NOAA Buoy 2 where the numbers of recaptures are highest.

Table III. Observed (Roman type) and predicted (*italic type*) tag transfers from the $M_2Q_2T_2$, n = 134 model. The rows (from) are tag-release sites and the columns are recapture sites.

	Recapture Sites											
From	All		Cross		B2		B3+B4		FADs		Other	
Bigeye												
All	194	*195.42*	96	*96.39*	76	*75.88*	8	*8.02*	7	*6.97*	7	*8.17*
Cross	112	*108.22*	91	*90.35*	8	*8.22*	6	*2.69*	6	*5.66*	1	*1.30*
B2	72	*76.42*	4	*4.83*	68	*67.55*	0	*3.19*	0	*0.77*	0	*0.08*
B3+B4	4	*4.01*	1	*1.21*	0	*0.11*	2	*2.14*	1	*0.54*	0	*0.01*
FADs	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*
Other	6	*6.77*	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*	6	*6.77*
Yellowfin												
All	127	*127.43*	92	*92.40*	12	*11.92*	6	*6.00*	10	*9.97*	7	*7.14*
Cross	102	*99.95*	90	*88.28*	2	*1.96*	4	*3.38*	4	*4.59*	2	*1.74*
B2	20	*18.91*	2	*2.50*	10	*9.92*	2	*1.44*	5	*4.20*	1	*0.84*
B3+B4	1	*4.05*	0	*1.62*	0	*0.04*	0	*1.18*	1	*1.18*	0	*0.04*
FADs	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*
Other	4	*4.52*	0	*0.00*	0	*0.00*	0	*0.00*	0	*0.00*	4	*4.52*

The time of recapture can be examined from two different points of view, absolute, from the calendar date of the first tag release (history), and relative, from the time of release of the recaptured tag (time at liberty). *Figure 2* shows the tag recapture histories at Cross Seamount. The most intense tagging and, consequently, most of the recaptures occured in the fourth quarter of 1996. Recaptures as a function of time at liberty are shown in *figure 3*. The agreement between predicted and observed recaptures is good for predictions greater than one tag. The longer persistence of tagged bigeye at Cross Seamount relative to yellowfin is evident in this figure.

The effort deviations modify the observed fishing effort in the direction of a value that would best predict the observed tag recaptures. These changes can be seen in *figure 4*. The effects of the effort deviations are small in most time periods, except in June and December 1996.

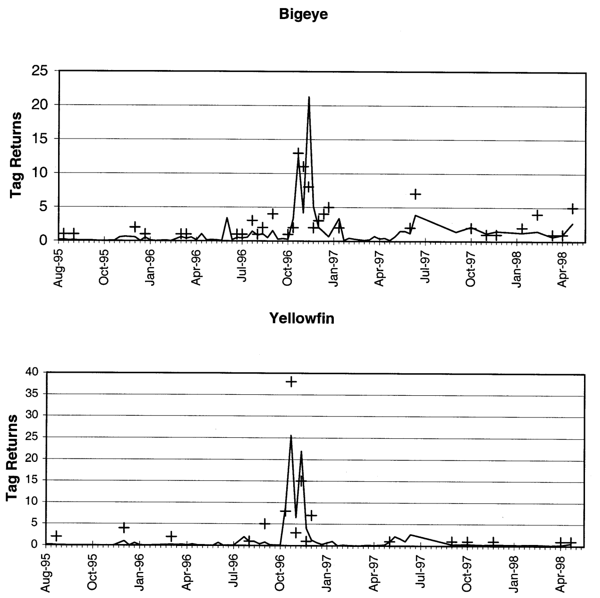

Figure 2. Bigeye (upper) and yellowfin (lower) tag recapture history at Cross Seamount. Solid line indicates predicted and + symbols indicate observed recaptures.

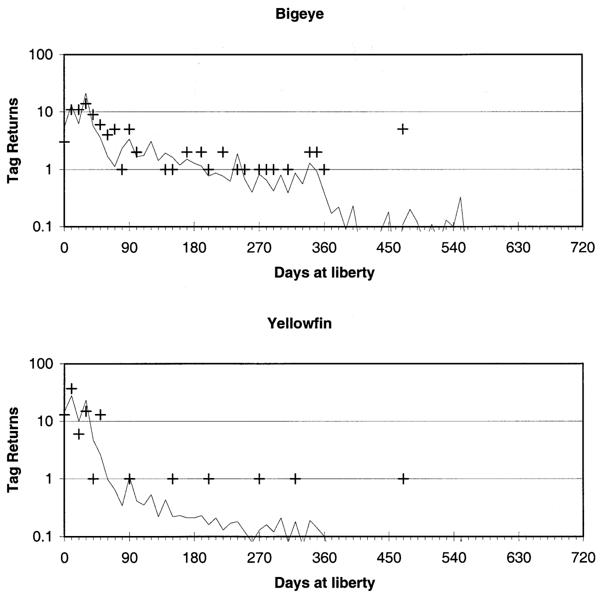

Figure 3. Bigeye (upper) and yellowfin (lower) tag attrition plots for recaptures at Cross Seamount. Solid line indicates predicted and + symbols indicate observed recaptures.

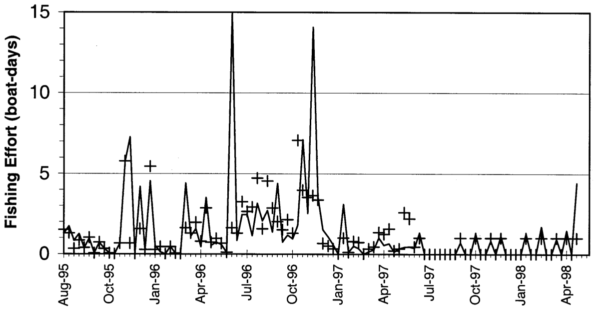

Figure 4. Effort history at Cross Seamount. Symbols indicate the observed fishing effort in boat-days fished. Solid line indicates the effective fishing effort computed using the effort deviations.

The average gross attrition rate for species *s* and site *i* can be defined as :

$$\bar{Z}_{s,i} = \bar{f}_{si} + \sum_j T_{sij} + M_s \qquad (7)$$

where $\bar{f}_{si}$ is the average fishing mortality assumed to be equal to q_{si} since the average normalized fishing effort = 1. Persistence is more intuitively expressed as half-life, the number of days required for half the population to dissappear, equal to $-\ln 1/2/\bar{Z}_{si}$. The estimated average gross attrition rate, half-life, and attrition components for bigeye and yellowfin at Cross Seamount are given in *table IV*. Bigeye are much more persistent at Cross Seamount than yellowfin. The estimated half lives of bigeye and yellowfin at Cross Seamount are 97.6 (± 18.5) and 18.3 (± 4.1) days respectively, where the number between parentheses is the standard deviation of the estimated half life. Natural mortality rates for the two species are similar, but both fishing mortality and emigration rates are lower for bigeye than for yellowfin. Nevertheless, the harvest ratios at Cross Seamount (proportion of attrition attributable to fishing) for both species are approximately 5 %.

The estimated values of the transfer rates are presented in *table V*. The rates of transfer of both species from the offshore sites to the inshore fads, $T_{i,4}$; $i = 1,2,3$ are much lower than the transfer rates to other recapture sites.

4. DISCUSSION

Analysis of the dynamics of the tuna populations at Cross Seamount was the primary motivation for the work described in this paper. Few tags were released at other sites and the number of recaptures at other sites was low. Therefore this discussion is largely confined to Cross Seamount results.

The estimated half-life of bigeye at Cross Seamount is roughly five times longer than that for yellowfin (*table IV*), strongly supporting the conclusion of Holland et al. (1999) that the bigeye population at Cross Seamount is much more persistent than the yellowfin population. The ability to resolve this gross attrition rate into its components allows us to draw conclusions about the dynamics and behavior of the two populations of fish at Cross Seamount.

The parameter *M* in equation (3) and in most other fisheries models represents losses from the population that cannot be attributed to specific processes and is dubbed “natural” mortality. In fact natural mortality in fishery models is not a single process (Beverton and Holt, 1957). In equation (3), natural mortality represents the losses of tagged fish from the population at a specific site that cannot be attributed to fishing or movement to other sites. Thus it includes emigration outside the model domain to areas where there may be no fisheries, recaptures which are not reported, and tag shedding. Natural mortality is a critical parameter for stock assessment modeling, and assessment efforts for bigeye have been particularly hampered by the lack of estimates of *M* (IATTC, 1997). Hampton (2000) estimated natural mortality for skipjack, yellowfin and bigeye in the western central Pacific using tag recapture methods and found that *M* varies with size. The bigeye tagged in this study were predominantly between 35 cm and 65 cm in fork length, and yellowfin ranged between 40 and 70 cm (Itano and Holland, 2000). We estimate natural mortality for bigeye and yellowfin to be 0.00274 day^{-1} (1.0 yr^{-1}) and 0.00323

Table IV. Estimates of attrition components at the Cross Seamount site with standard deviations of the estimates. The ratios are the ratio of the attrition component to the total attrition. Attrition rate components in day^{-1}; half life in days; ratios are dimensionless.

	Bigeye	Yellowfin
Average Gross Attrition ($\bar{Z}_{s1}$) (day^{-1})	0.00710 ± 0.00135	0.03782 ± 0.00853
Half Life (days)	97.6 ± 18.5	18.3 ± 4.13
Natural Mortality (M_s)	0.00274 ± 0.00135	0.00323 ± 0.00126
Catchability (q_{s1})	0.00033 ± 0.00006	0.00201 ± 0.00053
Emigration $\left(\sum_j T_{s1j} \right)$	0.00402 ± 0.00161	0.03257 ± 0.00810
Mortality Ratio $\left(M_s / \bar{Z}_{s1} \right)$	0.387 ± 0.185	0.086 ± 0.037
Harvest Ratio $\left(q_{s1} / \bar{Z}_{s1} \right)$	0.04654 ± 0.00751	0.05316 ± 0.00911
Emigration Ratio $\left(\sum_j T_{s1j} / \bar{Z}_{s1} \right)$	0.566 ± 0.186	0.861 ± 0.038

Table V. Estimated transfer coefficients from the full $M_2Q_2T_2$, n = 134 model. The rows (from) are tag-release sites and the columns (to) are recapture sites. Note that transfer coefficients designated “0” were not estimated.

	To				
From	Cross	B2	B3+B4	FADs	Other
			Bigeye		
Cross	0	0.00096	0.00289	3.12×10^{-5}	0.00014
B2	0.00182	0	0.01472	7.54×10^{-9}	9.43×10^{-8}
B3+B4	0.00037	0	0	5.55×10^{-6}	0
FADs	0	0	0	0	0
Other	0	0	0	0	0
			Yellowfin		
Cross	0	0.00335	0.02630	2.57×10^{-5}	0.00290
B2	0.00066	0	0.00914	0.00020	0.00139
B3+B4	0.00084	0	0	4.67×10^{-5}	0
FADs	0	0	0	0	0
Other	0	0	0	0	0

day^{-1} (1.2 yr^{-1}) respectively. These estimates agree closely with Hampton’s.

Although the model fits the data better with separate values of natural mortality for each species, the numerical values of the estimates are similar $M \sim 0.003$ day^{-1} and their standard deviations are high. In the current model, M is common to all sites and represents the general loss rate from the system.

Given the results of Holland et al. (1999), it is not surprising that the two species of fish have a similar estimate of M. In relative terms, natural mortality accounts for about 39 % of the total losses of bigeye from Cross Seamount and about 9 % of the losses of yellowfin.

The catchability coefficient, q_{si} is the proportion of the population caught by one unit of fishing effort. Since fishing effort is normalized to its average, q_{si} is also a measure of average fishing mortality. Yellowfin and bigeye are caught using the same fishing gear at Cross Seamount, but bigeye catchability is only 16 % that of yellowfin, suggesting that somehow bigeye are less vulnerable to the gear than yellowfin. However, since the bigeye outnumber yellowfin in the catch (Itano and Holland, 2000), it is possible that the bigeye population is larger than the yellowfin population but only a portion of the bigeye population is accessible to the gear through variability in both time and space. For both species, fishing accounts for about 5 % of the total losses from Cross Seamount. The total instantaneous rate of emigration away from Cross Seamount, $\sum_j T_{sij}$, is much higher for yellowfin than for bigeye, reflecting the shorter half life. Emigration accounts for 86 % of yellowfin and 57 % of bigeye losses from Cross Seamount. Some transfer rates are very close to zero and it is possible to eliminate some transfer coefficients, i.e. require them to be zero. Agreement between observed and predicted values can be improved by arbitrarily setting small values of T_{ij} to zero and eliminating them from the estimation procedure. However, there is no a priori ground for deciding which parameters to eliminate, and the procedure seems difficult to justify.

The Cross Seamount tagging study was motivated by several management questions concerning what was originally assumed to be a fishery on juvenile yellowfin tuna. One of the original concerns is the possibility that large catches at Cross Seamount and the weather buoys might have adverse impacts on the yellowfin fishery operating at FADs closer to the shore in the main Hawaiian Islands. Early in the study, it became clear that the largest component of the Cross Seamount catch is bigeye and that yellowfin comprises only about 20 – 30 % of the total, so that concerns over yellowfin were less acute. Our results show that the exchange rates of both species (*table IV*) from Cross Seamount to the inshore FADs are very low, $\sim 10^{-5}$ day^{-1}. Thus, tuna populations at Cross Seamount are not significant sources of recruitment of fish to the inshore FADs. It is unlikely that large catches of either yellowfin or bigeye at Cross Seamount are having any impact on the inshore fisheries unless the residence time at inshore FADs is very long.

The second major concern is that large catches at Cross Seamount are depleting the “resident” population at Cross. Our results indicate that catches of both species only account for about 5 % of the total population turnover. The estimated natural mortality rate for both fish is quite high. The value of 0.003 day^{-1} is equivalent to an annual rate of about 1.0. Such a high rate of natural mortality makes it unlikely that many of these fish would survive to recruit to fisheries on adult fish. High emigration and natural mortality rates make it hard to support the assumption that the Cross Seamount tuna populations are “resident”. Furthermore, catches that might be considered “large”, are small in relation to the other sources of mortality in the local population.

The Hawaii-based longline fleet depends heavily on catches of large yellowfin and bigeye tuna in the fishing grounds surrounding the Hawaiian Archipelago. A third concern is the possibility that large catches of juvenile fish at Cross Seamount are reducing recruitment of adult fish to the longline fishery. Only a few of the tagged fish released at Cross Seamount during the period of this study were recaptured by longliners making direct estimation of exchange rates impossible. However, the high rates of natural mortality for both species indicate at only about 10 – 20 % of the fish of the size of those tagged at Cross Seamount will survive to reach the size of those caught by longliners, suggesting that catches at Cross Seamount would not affect recruitment to the longline fishery.

As far as is known, there are populations of tuna at Cross Seamount throughout the year. Therefore it seems reasonable to postulate that fish are recruited, or immigrate, to Cross Seamount from unknown sources. The picture that emerges of the Cross Seamount tuna aggregation is that of a highly labile population in which individuals arrive (possibly as returnees or immigrants from the weather buoys), remain a few days or weeks, and then leave.

More than 10 000 additional tuna have been tagged since January 1998. The additional recaptures from these releases will enable us to repeat this analysis and to extend the results significantly. In the future, we intend to test the conclusions reached in this analysis, to more accurately estimate residence patterns in the inshore FADs, and to estimate the recruitment rate to the longline fishery.

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