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EXPERIMENT

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INTRODUCTION

The tuna fishery in the western Pacific Ocean (WPO: 40°N-40°S, 120°E-150°W), with an estimated catch in 1991 of 1.4 million t (Lawson 1992), is the largest in the world, now accounting for about 50% of the global production of primary market species. Skipjack (*Katsuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*) dominate the catch, comprising 69% and 26%, respectively, of 1991 landings. Large purse seine vessels from the United States, Japan, Korea, Taiwan and others are the most important component of the fishery in terms of catch, operating mainly within the 10°N-10°S band, an area termed the western tropical Pacific (WTP). Skipjack and, to a lesser extent, yellowfin are also caught by long-range pole-and-line vessels from Japan and in domestic fisheries using various gears in Indonesia, Philippines, Solomon Islands, Kiribati and Fiji. Yellowfin are also caught, generally at larger size, by longliners.

The yellowfin catch has almost doubled in the past ten years, with most of the increase occurring since 1988 (Figure 1). Catches in the early 1980s had averaged about 200,000 mt, and this, along with stable catch rates in most of the fisheries, led Suzuki et al. (1989) to suggest that catches of this magnitude were sustainable. The rapid increase in catch since 1988, although not accompanied by a decline in catch rates (Lawson 1993), caused concern because little was known of the population dynamics of western Pacific yellowfin, and therefore the response of the stock to these catches could not be predicted.

It was therefore fortuitous that the South Pacific Commission undertook a large-scale tagging project in the WTP at the time that this increase in catch was taking place. The Regional Tuna Tagging Project (RTTP), which was directed principally at yellowfin and skipjack, was designed to provide information on the stock dynamics and exploitation rates of those species. Tagging began in mid-1989 and continued until December 1992. During this time, 40,352 yellowfin were tagged over a large area of the WTP (Figure 2). The distribution of releases covered most areas of intense yellowfin catch (Figure 3), and the distribution of tag recoveries (Figure 4) reflected both the distribution of releases and the distribution of catch. As at 12 May, there had been 4,725 (11.7%) confirmed recaptures.

In this paper, these tagging data are analysed, using a simple tag-attribution model, to give estimates of yellowfin mortality rates, throughput and standing stock available to the surface fisheries in the WTP. On the basis of the estimated model parameters, conclusions regarding the long-term exploitation potential of the stocks are drawn.

The area to which the analysis refers is not precisely defined, but is basically the area encompassed by the tag recaptures. This area includes the Philippines and eastern Indonesian domestic fisheries, as well as including most of the catch by the international purse seine fleet and Pacific Island domestic fisheries. The data set analysed consists of yellowfin larger than 40 cm released from July 1989 to July 1992 (24,318 releases) and associated recaptures until 30 September 1992 (2,341 recaptures). The length restriction was introduced to avoid complications associated with possibly high natural mortality and tagging-induced mortality rates of very small yellowfin. The cut-off dates were chosen to allow a reasonable time for recently recovered tags to be returned. Time series of catch data are analysed in conjunction with the tagging data.

TAG-ATTRITION MODEL

Two equations define the model, as follows:

$$\hat{r}_{ij} = N_i e^{-\sum_{k=i}^{j-1} F_k + (j-1)M + S + G} (1 - \alpha)(1 - \delta)\beta \frac{F_j}{F_j + M + S + G} \left[1 - e^{-(F_j + M + S + G)} \right] \quad (1)$$

$$C_j = P \frac{F_j}{F_j + M} \left[1 - e^{-(F_j + M)} \right] \quad (2)$$

Equation (1) predicts our experimental observations, the numbers of tag returns \hat{r}_{ij} , by month of release (i) and recapture (j), as a function of the model parameters, the input parameters and the input data. If only this equation was used, the model parameters would be the natural mortality rate M (assumed constant over time) and the fishing mortality rate by month F_j . In order to avoid having j independent parameters in F , we re-parameterise F_j as a function of the standing stock P , M and the monthly catch C_j . Therefore, using the two equations, the model parameters become M and P , and the input data are the monthly tag release numbers N_i and the monthly catches C_j . The input parameters account for other sources of tag loss and are not generally estimable from the tagging and catch data, as they are almost totally confounded with the fishing mortality rate or the natural mortality rate. These parameters are the immediate tag-shedding rate α , the continuous tag-shedding rate S , the immediate tagging mortality rate δ , the continuous tagging mortality rate G and the reporting rate β . Treatment of these parameters is described under "Assumptions relating to input parameters".

The model parameters were estimated by maximum likelihood using a multinomial likelihood function. The negative log likelihood ℓ of the data r_{ij} with respect to the model parameters was evaluated by the equation (ignoring all constant terms)

$$\ell = \sum_{i=1}^u \log \left[1 - \sum_{j=1}^t P(r_{ij}) \right] + \sum_{j=1}^t r_{ij} \log [P(r_{ij})] \quad (3)$$

where u is the number of release sets (months), t is the number of months from the first tag-release month to the end of the experiment and the recapture probabilities $P(r_{ij})$ are given by $\frac{\hat{r}_{ij}}{N_i}$.

A nonlinear optimisation algorithm was used to find the set of model parameters that minimise ℓ and hence maximise the likelihood. For this analysis, we used the simplex algorithm of Nelder and Mead (1965).

Having derived the M and P estimates, other quantities of interest, such as average fishing mortality \bar{F} , throughput T and harvest ratio H , were determined according to the following equations:

$$\bar{C} = P \frac{\bar{F}}{\bar{F} + M} \left[1 - e^{-(\bar{F} + M)} \right] \quad (4)$$

$$T = P \left[1 - e^{-(\bar{F} + M)} \right] \quad (5)$$

$$H = \frac{\bar{F}}{\bar{F} + M} \quad (6)$$

Note that equation (4), like equation (2), must be solved for \bar{F} using a numerical method such as the Newton-Raphson. Assuming that T and M will remain constant over some reasonable range of \bar{C} , we can calculate values of P and H associated with different levels of \bar{C} . By applying criteria to define a minimum acceptable P or a maximum acceptable H , we can, under these assumptions, get some indication of the exploitation potential of the stock.

MODEL ASSUMPTIONS

Assumptions relating to model structure

Temporal structure

This version of the tag-attrition model is essentially an equilibrium model – we assume that M and P are constant over time (although F can vary). This implies that losses from the population through natural mortality and fishing are exactly balanced by recruitment. Kleiber et al. (1987) found that, for a similar model applied to western Pacific skipjack, only extreme violations of this assumption invalidated the conclusions. In particular, they found that H was quite robust to cyclical variation in P . We tested for non-equilibrium conditions by generalising the model such that the parameter P is replaced by two parameters, an initial population biomass P_0 and a recruitment rate R . This model structure allows P to increase or decrease during the course of the experiment. In this case, equation (2) is replaced by

$$C_j = \frac{F_j}{F_j + M} \left[1 - e^{-(F_j + M)} \right] P_0 e^{-\sum_{k=1}^{j-1} F_k + (j-1)M} + R \left[\sum_{n=1}^{j-1} e^{-\sum_{k=n}^{j-1} F_k + (j-n)M} + 1 \right] \quad (2a)$$

A likelihood-ratio test showed that the improvement in fit to the yellowfin data obtained using the more complex model was not significant. Under these circumstances, the simpler, equilibrium model is preferred on statistical grounds. While this test is not conclusive, it suggests that there is not a strong signal in the data that would lead us to reject the equilibrium assumption.

Spatial structure

The estimated parameters and derived quantities represent average conditions across the area of the tagging experiment (approximately 10°N–10°S, 120°E–170°W). In reality, there may be areas of higher or lower natural and fishing mortality rates, stock densities, etc, but these features have not been incorporated into this model. Our main interest here is an overall picture of the aggregate stock and its exploitation.

For the dynamics of the tagged yellowfin to be extrapolated to the stock as a whole, it must be assumed that the probabilities of capture of tagged and untagged fish are the same. This might not be the case if, for example, most releases were made in the vicinity of the fisheries and a large number of short-term recaptures were generated before the tagged fish had a chance to move away from the release site. Under these circumstances, biased parameter estimates would likely result. If the model had spatial structure and a series of P 's were estimated for each spatial stratum, then we would only need to assume that the capture probabilities were the same within strata. The lack of spatial structure in our model means that the necessary assumptions are somewhat more demanding. We countered this problem in two ways. Firstly, at the experimental level, we attempted to release tagged yellowfin throughout the geographical range of the fishery, thus sampling a range of exploitation profiles. In other words, tagged yellowfin were released in areas that experienced very different fishing intensities, from high effort in the immediate vicinity to no effort at all within a radius of 100 nmi. or more. Secondly, at the analytical level, we allowed for a mixing period after tagging; movement rates of tagged yellowfin suggested that four months is generally sufficient for substantial mixing to take place. Recaptures made during the mixing period were not allowed to impact the parameter estimation. We did this by excluding the recaptures made during the mixing period from the likelihood function, but used these

recaptures and the model parameters to calculate the number of tagged fish alive immediately after the mixing period. This essentially means that we let $\hat{r}_{ij} = r_{ij}$ for the first four recovery months of each release set.

Size structure

The model does not consider size structure, therefore we make the implicit assumption that the estimated mortality rates are size independent. Given that this is probably not the case, we should therefore interpret these rates as weighted averages, the weights being automatically determined by the size distributions of releases, the catch and the population. Simulations have been carried out to determine the effects of these factors on the parameter estimates (see Appendix). The simulations suggested that the size distribution of releases has little impact on the parameter estimates but showed that the size distribution of the catch in relation to that of the population, ie. size selectivity, may well have an effect. In particular, it is clear that the tagging experiment can only measure that component of the population available to the fisheries, therefore the estimates of P , F , H and T will only pertain to that available component. Depending on the severity of size selection, the effects on these parameters can be substantial. If size selection occurs mainly during the recruitment process, this effect on the estimates will not be of concern as most fisheries analyses only deal with the post-recruit component of the population. If size selection also occurs at larger sizes, this may affect our interpretation of the parameter estimates in relation to stock assessment; the parameter estimates would tend to give an overly pessimistic view of the status stock. This is because such size selection would effectively provide a buffer to the stock that the tagging experiment cannot "see".

Assumptions relating to input parameters

The valid use of a tag-recapture experiment to obtain information on fishing mortality is critically dependent on all sources of tag loss being accounted for. These sources of tag loss are the input parameters in equation (1), α , S (tag-shedding parameters), δ , G (tagging mortality parameters) and β (reporting rate).

Tag shedding

We estimated tag-shedding rates from returns of double-tagged yellowfin. Double tagging, in which one tag is placed on either side of the fish and anchored in the pterigiophores in the same fashion, was carried out at various times throughout the RTTP. The models and fitting procedures described by Hampton and Kirkwood (1990) were used to estimate tag-shedding rates. Of the four models described by Hampton and Kirkwood (1990), model 2 was found to be optimal for the yellowfin double-tagging data. This model has the form

$$Q_t = (1 - \alpha)e^{-St} \quad (7)$$

where Q_t is the probability of a tag being retained at time t after release. Fitting this model to the yellowfin double-tagging data, which consist of 166 returns with two tags and 27 returns with one tag, provides estimates of α and S (Table 1).

Tagging mortality

High quality control standards during the tagging operation were applied so as to minimise stress, and resulting mortality, on the fish. Observations of tagged fish behaviour immediately after release suggest that stress is minimal. There have been numerous instances of newly tagged tuna immediately re-joining the feeding school and being recaptured within seconds of release. The resumption of normal feeding behaviour strongly suggests that tuna are not unduly affected by capture and tagging. Observations of very high recapture rates (>50%) for some schools tagged in the vicinity of fishing activity support this assertion. While the above is generally true, the occasional tagged tuna, usually of small size, was observed to swim rapidly along the surface in an apparently distressed state after tagging. On several occasions, these fish were observed to be eaten by sharks. The rejection of yellowfin

<40 cm FL at release from this analysis would have minimised this problem. Nevertheless, to be conservative, we have assumed an immediate tagging mortality rate of 0.05 in this analysis.

There is less evidence regarding a long-term, or continuous, mortality associated with bearing tags. However, tag insertion wounds appear to heal quickly and cleanly, and have not been observed to be infected. Increased predation mortality associated with bearing tags is unlikely in rapidly-swimming tuna (apart from the rare instances where the tuna were distressed, as noted above). In the absence of any evidence to the contrary, we have assumed G to be zero.

Non-reporting of tags

Non-reporting of tags is likely to affect every tagging experiment where tag recoveries are generated by a commercial or recreational fishery. During these experiments, various incentives, such as tag rewards and lotteries, were used to promote the return of tags. Nevertheless, some non-reporting will have occurred and must be accounted for in the parameter estimation.

One method used to estimate the reporting rate is tag seeding. This involves the tagging of a sample of dead fish in the catch before tag detection processes begin. If seeding is carefully and discreetly carried out, the proportion of seeded tags returned is an estimate of the reporting rate. During the RTTP, a thorough tag-seeding programme was carried out, with selected observers on US, Japanese and Taiwanese purse seiners tagging up to five fish caught during the course of a voyage. Seeding was generally carried out discreetly on the main deck while sampling, or on the well deck immediately before fish stowage. As almost all purse-seine-caught tagged fish are detected during vessel unloading or processing in canneries, the seeded tags were thus available to all detection processes and were indistinguishable from genuine tags. Seventy-two such individual experiments have so far been carried out, seeding a total of 343 tags (for yellowfin and skipjack combined) and covering all of the major unloading locations for western-Pacific-caught tuna. These experiments will continue while significant numbers of genuine tags continue to be returned. The interim recovery rate of seeded tags is currently 0.70, which is the value of β used in these analyses. β is assumed to be time invariant.

Emigration from the area of the fishery

While not explicitly parameterised in the model, emigration from the fishery is totally confounded with M in this model. Of course, the larger the area covered by the tagging experiment, the less likely this is to be a problem. On the basis of observed movements of tagged yellowfin, we consider that significant emigration of yellowfin, for example to the eastern Pacific or to the Indian Ocean, from the area of the western Pacific fisheries is unlikely to be a significant source of tag loss.

Reduced vulnerability of larger yellowfin

In a similar fashion to emigration, reduced vulnerability of larger yellowfin would produce a tag loss that is totally confounded with M . It has been suggested that the size composition of yellowfin caught by purse seiners is consistent with reduced vulnerability of medium-sized fish. Simulations have shown that this reduced vulnerability, even if only temporary, tends to positively bias the estimate of M (see Appendix). Although there was no evidence of reduced vulnerability in the yellowfin tag-attrition curve (see later), the possibility of such an effect cannot be totally discounted.

PRECISION OF ESTIMATES

We used bootstrap techniques (Buckland and Garthwaite 1991) to quantify the precision of the estimated parameters and related derived quantities. A stratified non-parametric bootstrap, in which 1,000 pseudo-data sets of an identical structure to the real data

were created by randomly sampling with replacement from the real data, was used to generate a multinomial sampling error.

The true confidence intervals of parameters and derived quantities should include the effects of uncertainties in the various input parameters and the data as well as those due to multinomial sampling error. In the case of the tag-shedding parameters, an independent parametric bootstrap, which simulated the binomial probability structure of the double-tagging experiment, was used to obtain 1,000 independent pseudo-estimates of the two tag-shedding parameters. Similarly, 1,000 pseudo-estimates of the reporting rate and immediate tagging mortality rate were obtained by random sampling from beta distributions with means of 0.7 and 0.05, respectively, and coefficients of variation of 10% and 5%, respectively. These coefficients of variation, while somewhat arbitrary, were chosen to reflect the degree of uncertainty that we feel is appropriate for the point estimates. In the case of the input data, it is reasonable to assume that the tag-release and tag-return numbers are not subject to error. However, the monthly catch is only approximately known, and is based on the best estimates of annual catches for the calendar years 1989-1992 apportioned equally to months in those years. We have therefore assumed that the estimates of annual catches are subject to independent, normally-distributed, random errors with coefficients of variation of 10%. We generated 1,000 pseudo-data sets of catch by sampling from the distributions of annual catch and apportioning these catches uniformly to months in the respective calendar years. Previous simulations have shown that random, month-to-month variation in catches does not affect the precision of parameter estimates (Hampton 1992).

The 1,000 sets of pseudo-estimates (tag-shedding parameters, reporting rate, immediate tagging mortality and catch data) were used, in turn, as the input parameters for the analysis of the 1,000 sets bootstrapped tagging data. 1,000 pseudo-estimates of model parameters and derived quantities were so obtained, and the 2.5% and 97.5% quantiles of their distributions used to approximate the 95% confidence intervals.

RESULTS

Model fit

The fitted model accurately describes the aggregate rate of tag return by period at liberty (Figure 5a). There is something of an anomaly in the plot by calendar month, with higher than expected returns during the first half of the experiment and lower than expected returns during the second half (Figure 5b). This could be due to inaccuracies in the assumed catches or variation in reporting rate, among other possibilities.

The fits to tag-return data for individual release months are more variable (Figure 6) – the fit is good for some months and poor for others. These anomalies in the fits are probably due to spatial and temporal variations in natural mortality, exploitation and population density that our model cannot consider. However, some of the deviations may be reduced with the incorporation of more recent tag returns and more accurate monthly catch data.

Parameter estimates

Estimates and 95% confidence intervals of model parameters, derived quantities and input parameters are given in Table 1. The estimate of M (0.098-0.12 mo⁻¹) is somewhat higher than the interim estimate reported in Hampton (1992), although the 95% confidence intervals overlap. Our estimate is also somewhat higher than most estimates for eastern Pacific yellowfin, eg., 0.053–0.075 mo⁻¹ (Hennemuth 1961) and 0.067 (Murphy and Sakagawa 1977). Average F is relatively low, resulting in an estimated harvest ratio of 0.16 (0.13-0.21). Annual throughput is substantially higher than the estimated standing stock and implies that the population available to the fisheries is replacing itself every 8 months on average. These stock dynamics suggest a productive resource capable of supporting large catches.

Impact of current exploitation

The most useful estimate for inferring the current impact of fishing on the yellowfin stock is the harvest ratio, which is simply an estimate of the proportion of total mortality due to fishing (and also the proportion of the total throughput, removed by fishing). The current estimate of yellowfin harvest ratio is 0.16 (0.13–0.22). Although there are no general biological criteria to indicate a maximum acceptable harvest ratio, values less than 0.5 are normally associated with fisheries that can sustain increased exploitation (Kleiber et al. 1987). We would certainly not expect recruitment overfishing to occur in tuna fisheries at harvest ratios of less than 0.5. On this basis, we conclude that the current impact of the fisheries on the western Pacific yellowfin stock is at most moderate.

Exploitation potential

While this is useful information and is reassuring to fisheries management agencies in the region and countries involved in the fishery, it would also be informative to be able to predict the impact of increased catches on the stock, and by so doing make informed judgements regarding exploitation potential. It is technically possible to extrapolate from the current situation, using the fitted model, if the estimated natural mortality rate and throughput are not affected by changes in exploitation. While such extrapolation may be useful, we must be careful not to extrapolate so far that we run the risk of violating these constant-rate assumptions. It is also necessary to remember that the predicted population responses are "average equilibrium responses" – in reality the population is affected by a range of seasonal, cyclical and random phenomena that our model cannot consider.

How far can we realistically extrapolate? The relationship between catch and fishing mortality in our model is such that, for very high levels of fishing mortality, the equilibrium catch approaches the throughput but can never exceed it (Figure 7). In reality, catches that approached this limit would quickly reduce the population to such an extent that the throughput could not be sustained because of recruitment failure. We therefore feel that it would be inadvisable to extrapolate beyond harvest ratios of 0.5. For harvest ratios <0.5 , the standing stock would be more than half its unexploited level and the constant rate assumptions should not be grossly violated.

Projections of standing stock and harvest ratio, and their 95% confidence intervals, were made over the range of equilibrium catch levels corresponding to average harvest ratios of <0.5 . As expected, the harvest ratio increases (Figure 8) and the standing stock decreases (Figure 9) with increasing equilibrium catch. The uncertainties in both quantities, as reflected by the 95% confidence intervals, increase with increasing catch.

There are many different criteria that could be applied to these relationships in order to nominate a "maximum safe" harvest. Two such criteria that are sometimes used in fisheries management are to (i) maintain a harvest ratio of no greater than 0.5 and (ii) maintain the standing stock at no less than half the level it would be in the absence of exploitation. To be at least 95% certain that these criteria would be met, we should choose catch levels in which not only the *average* harvest ratio or standing stock satisfies the relevant criterion, but also the extremities of the 95% confidence intervals. These criteria should constitute conservative definitions of "maximum safe" harvest. Using criterion (i), the maximum annual yellowfin catch would be about 800,000 mt (Figure 8). Criterion (ii) is slightly more conservative because of the larger confidence intervals on the standing stock estimates, and suggests a maximum catch of about 600,000 mt (Figure 9).

We should note that a decline in standing stock associated with increased catch would, if catchability remained constant, result in similar declines in CPUE, which may impact economic viability regardless of biological sustainability. However, compensatory increases in catchability might occur, eg. through yellowfin schooling behaviour or increasing catching efficiency, which would tend to maintain CPUE at high levels. At present, there is no basis for predicting an exact, or even average, response of CPUE to changing standing stock levels.

DISCUSSION

The simple tag attrition model used in this analysis does not account for spatial variation in the distribution of tagged and untagged fish nor in their pattern of exploitation. Neither does it consider the size or age structures of the tag releases, the catch or the population. We therefore need to think of the estimated parameters as quantities averaged both spatially and across sizes, and recognise that in reality there will be possibly large spatial and size-related variations in tuna abundance and mortality. The question is whether a simple model that ignores these features can accurately capture information on the aggregate population and average mortality rates. Various simulation studies have been carried out to investigate this question, and in particular to assess the effects of our experimental design (spatial and size distribution of releases) on the results of this aggregate-type analysis. This work is continuing, but preliminary results suggest that the lack of spatial structure in the model does not bias the estimates of average mortality rates and aggregate population size. This appears to be because of the wide spatial distribution of releases, rapid movement rates of both species and the allowance in the analysis of a sufficiently long period for mixing to take place. Similarly, the size distribution of releases does not appear to affect the accuracy of parameter estimates. However, the complex size selectivity of the diverse yellowfin recapture fisheries means we need to be careful in the interpretation of population size, fishing mortality and throughput estimates. These quantities pertain only to that portion of the population "seen" by the tagging experiment and are therefore measures of the "available" population and not the entire population. Ultimately, it is planned to develop models that explicitly incorporate spatial and size structure, however in the meantime, the simulation studies suggest that the simple model used here can provide useful information on the aggregate stock dynamics.

The results show that yellowfin are at most subject to only moderate exploitation pressure at the average annual catch levels pertaining during the course of the experiment (about 350,000 mt). There is clearly the potential for increased yellowfin catches on a regional scale from a biological perspective. On a smaller scale, there are some areas that are more heavily exploited than others (eg. in the Philippines, where the local tag recovery rate is now approaching 30%, compared to 5-15% for other areas of the western tropical Pacific); this potential is therefore not evenly distributed. Analyses of specific subsets of the data and the development of a spatial model will provide further information on exploitation potential in specific areas.

In the short term, economic considerations (primarily the depressed world tuna market) will probably limit further development of at least the purse seine component of the fishery. If and when further expansion of catches does take place, it will be important to collect catch, effort, size composition and other biological data necessary for the ongoing stock assessments that will complement the tagging-based analyses. This will be particularly important for the investigation of more complex problems involving fishery interaction and the effects of local exploitation.

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Table 1. Estimates and 95% confidence intervals of model parameters, derived quantities and input parameters for the western Pacific yellowfin tag attrition model.

	Mean	Lower 95% CI	Upper 95% CI
Model parameters			
Natural mortality rate (per month)	0.11	0.098	0.12
Standing stock (thousand mt)	1,431	1,032	1,837
Derived quantities			
Average fishing mortality rate (per month)	0.022	0.017	0.030
Harvest ratio	0.16	0.13	0.21
Throughput (thousand mt per month)	179	132	226
Input parameters			
Immediate tag-shedding rate	0.070	0.039	0.10
Continuous tag-shedding rate (per month)	0.0011	0.0000	0.0061
Reporting rate	0.70	0.55	0.83
Immediate tagging mortality	0.050	0.0014	0.18
Continuous tagging mortality (per month)	0	0	0

Figure 1. Yellowfin catches, by fishery in the western Pacific.

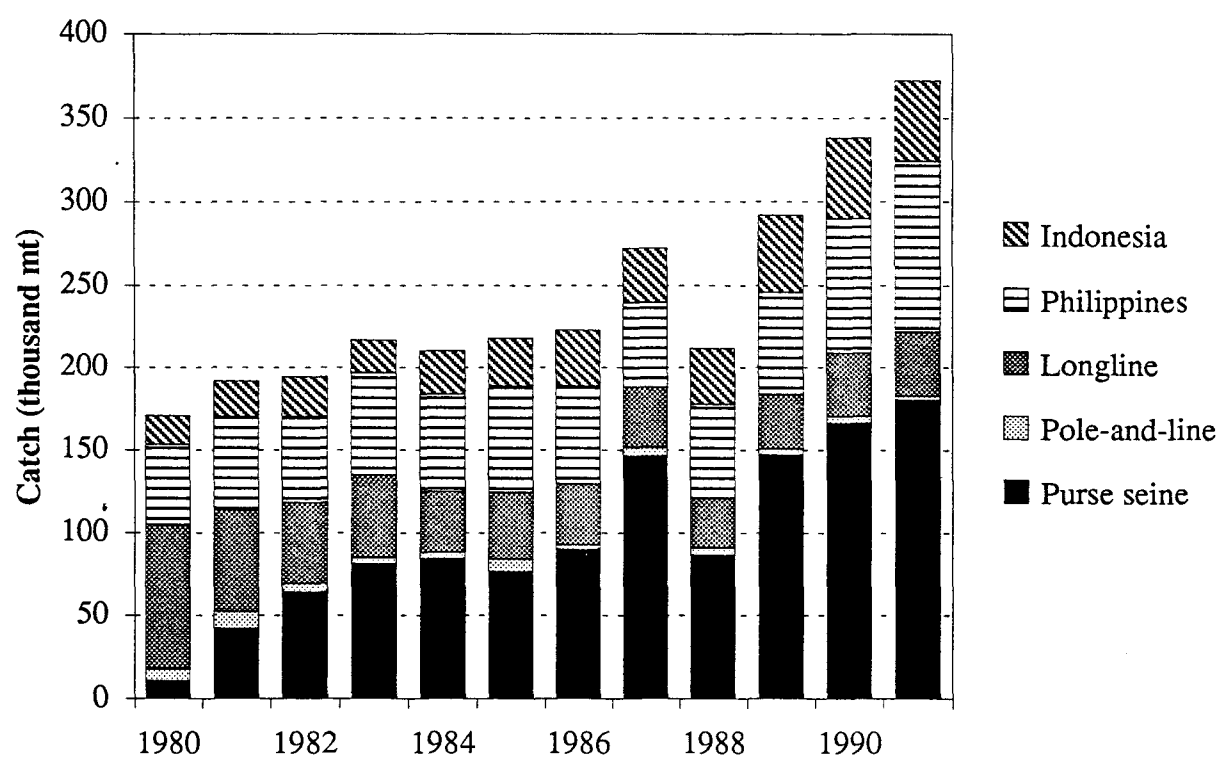


Figure 2. Geographical distribution of tagged yellowfin releases by the Regional Tuna Tagging Project.

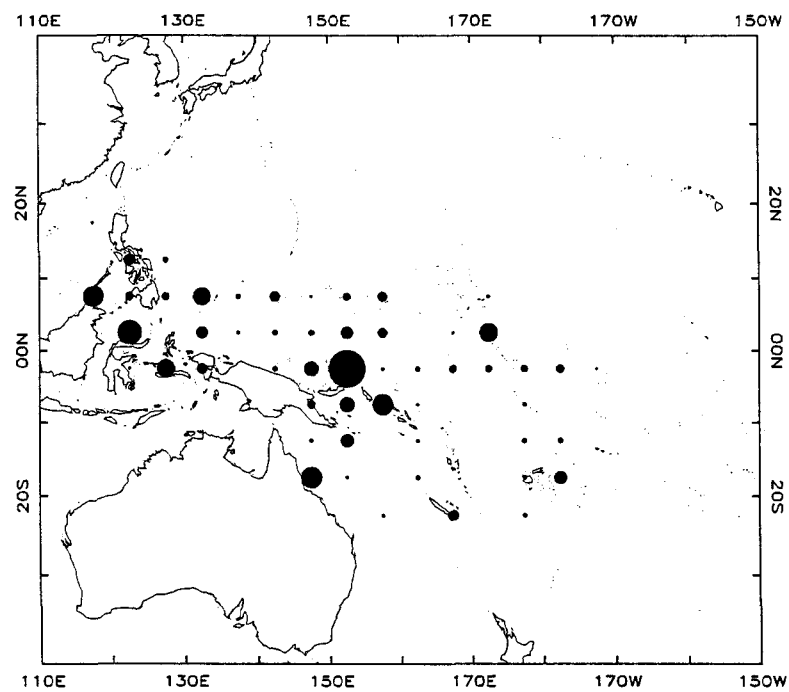


Figure 3. Geographical distribution of yellowfin catch in the western Pacific Ocean in 1990. The distribution of catches in eastern Indonesia and the Philippines is approximate.

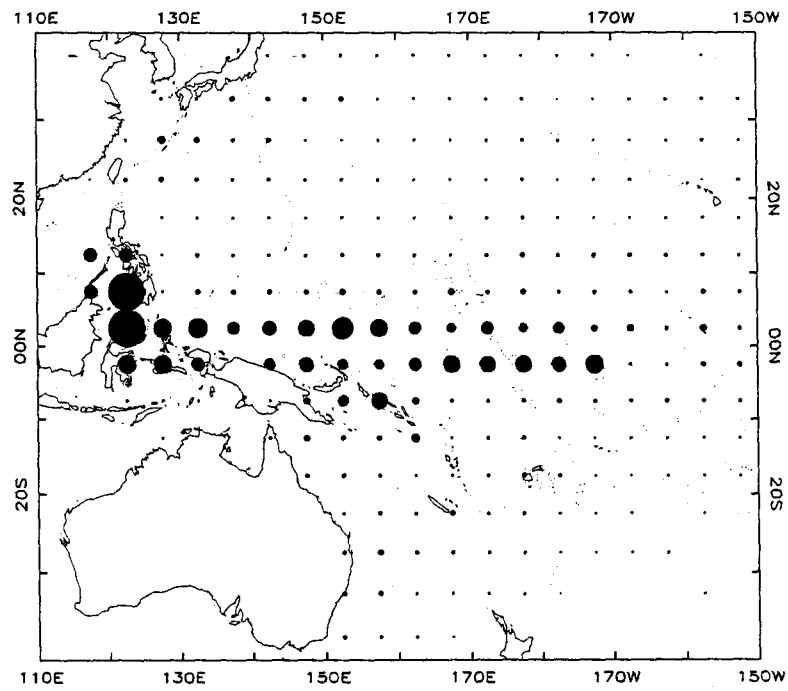


Figure 4. Geographical distribution of yellowfin tag returns with known recapture location and >120 days at liberty.

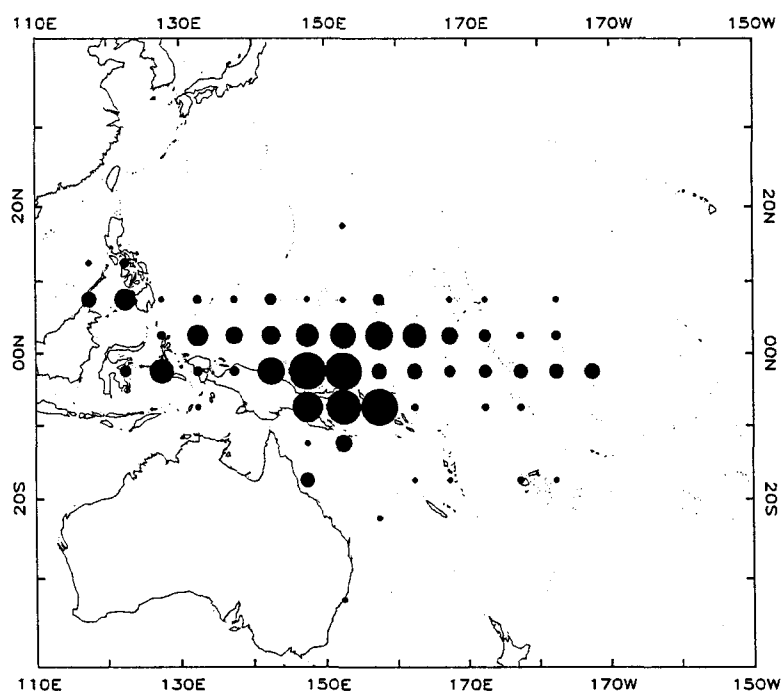


Figure 5. Tag returns by months at liberty (A) and by calendar months (B). The dots indicate the observed returns and the line represents the model predictions.

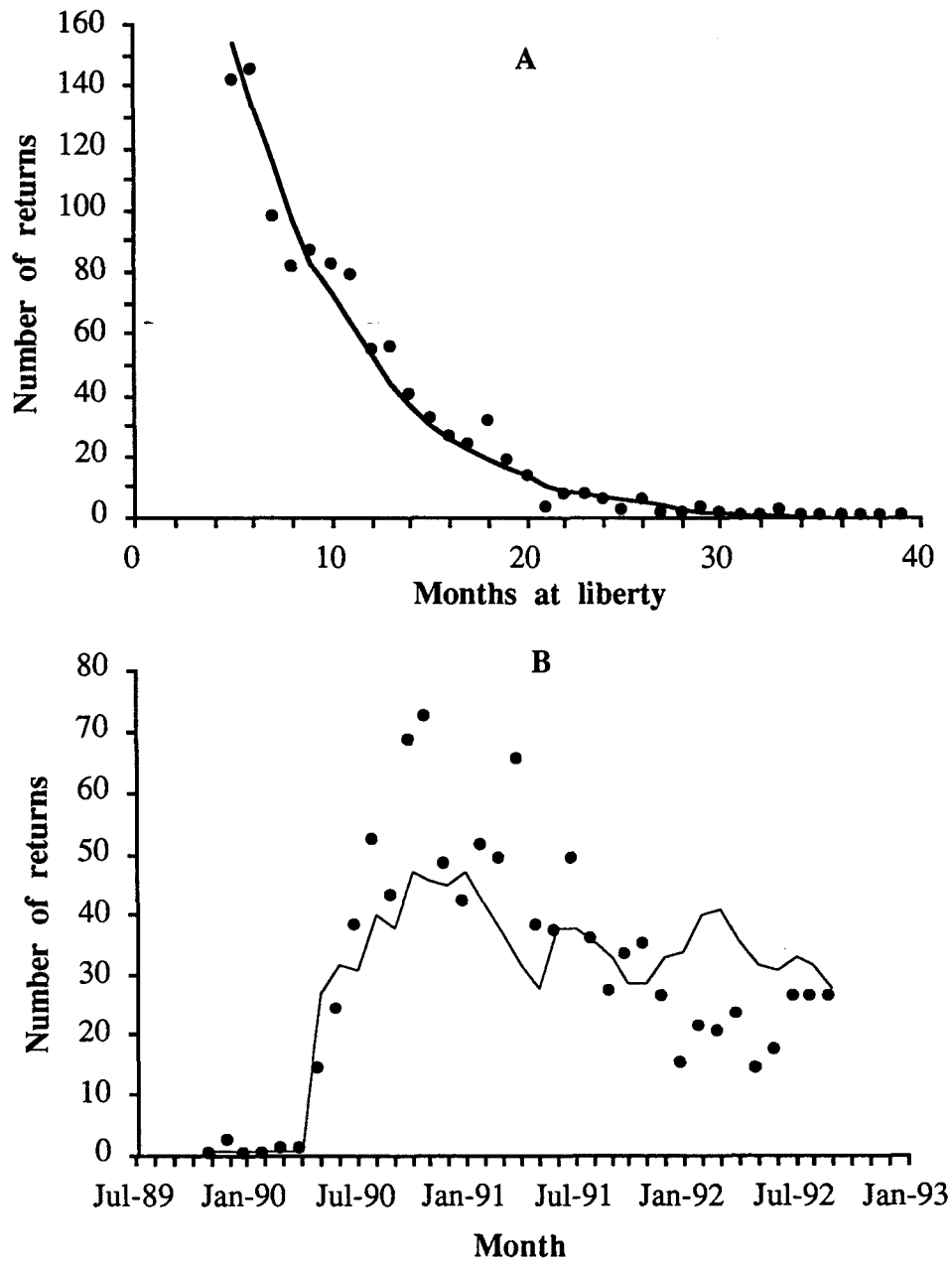


Figure 6. Tag returns by months at liberty (A) for selected release sets. The dots indicate the observed returns and the line represents the model predictions. The first four months of returns for each release set are not modelled.

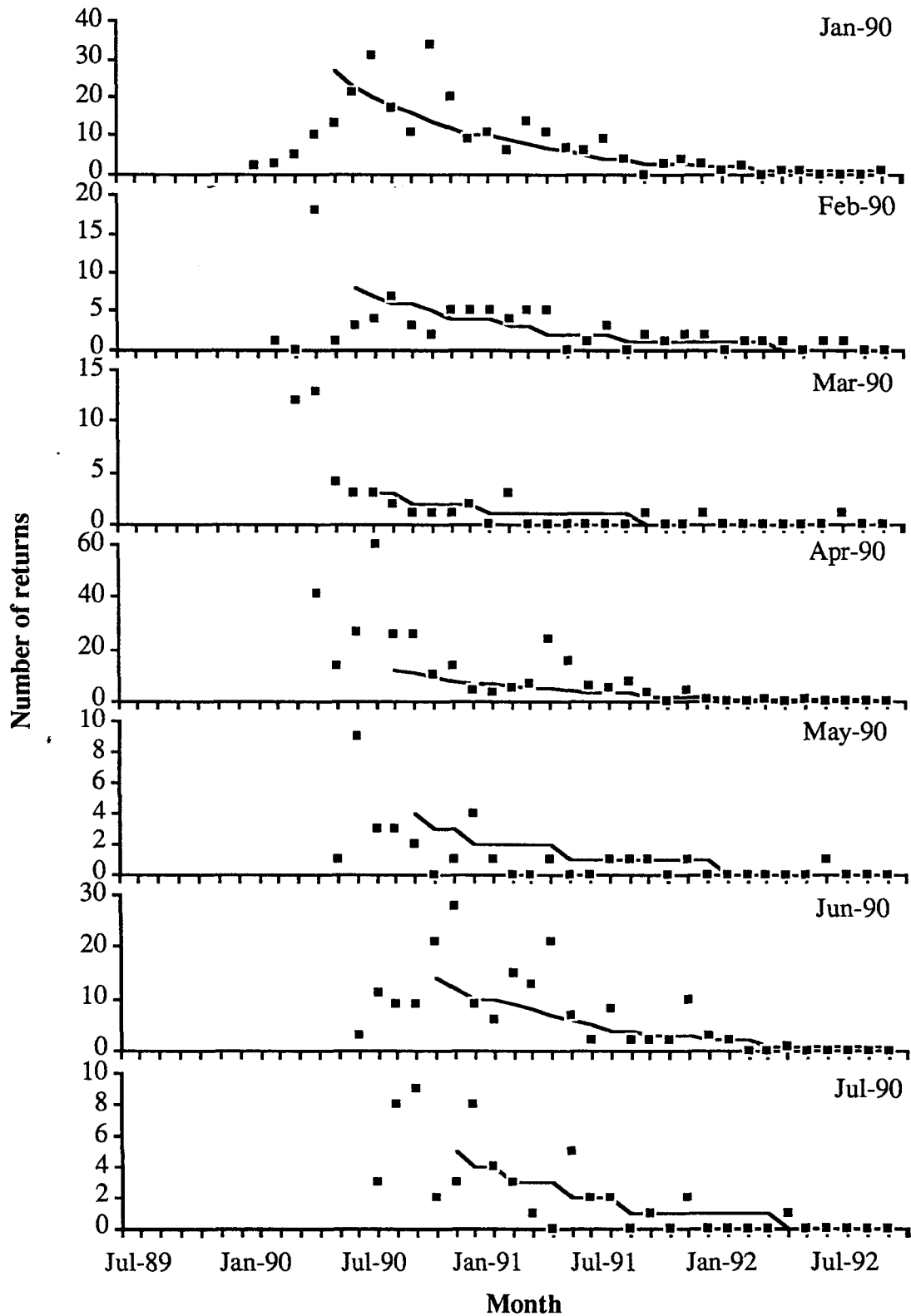


Figure 6. Continued

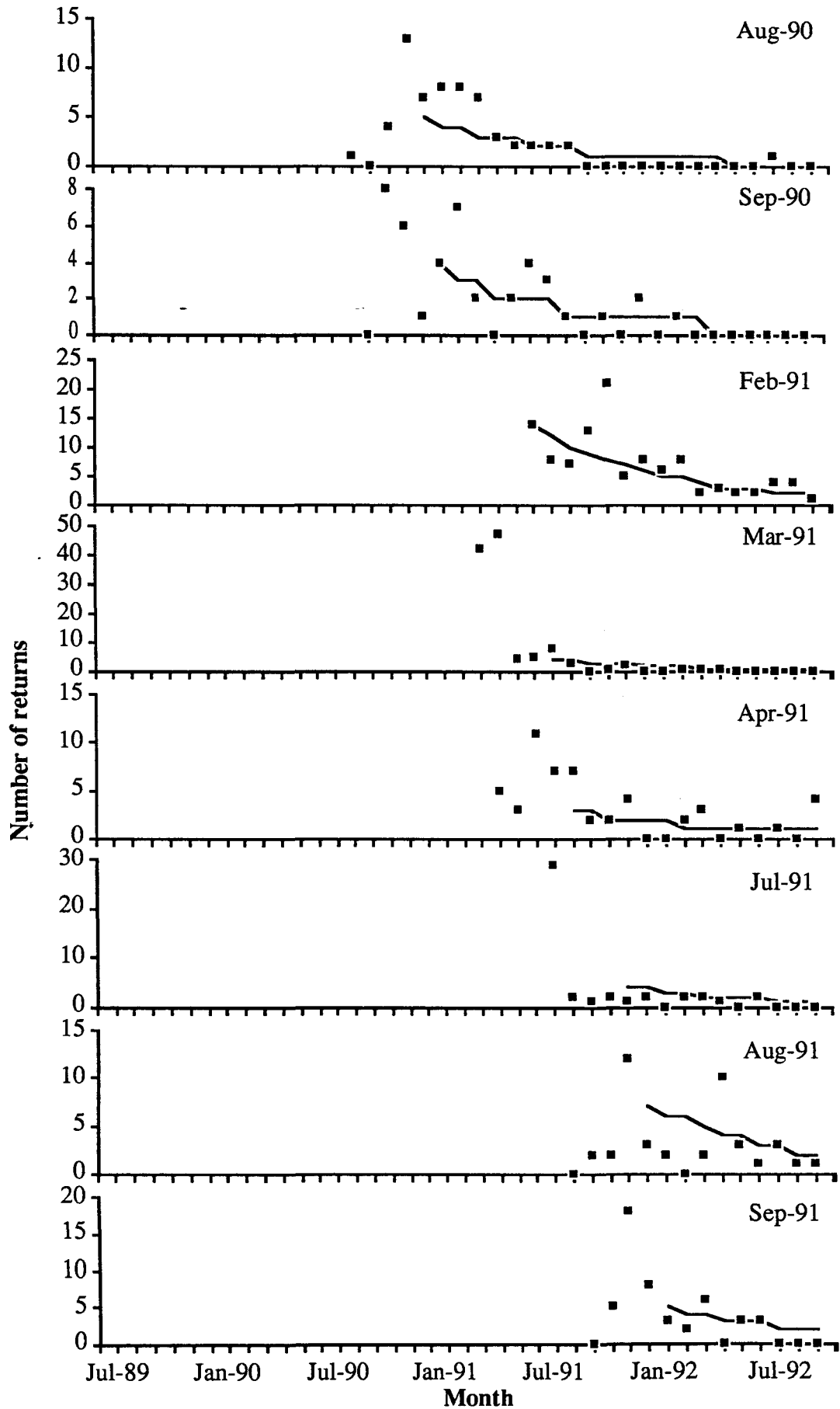


Figure 7. Relationship between yellowfin harvest ratio, fishing mortality rate and equilibrium annual catch, with assumptions of constant throughput and natural mortality rate.

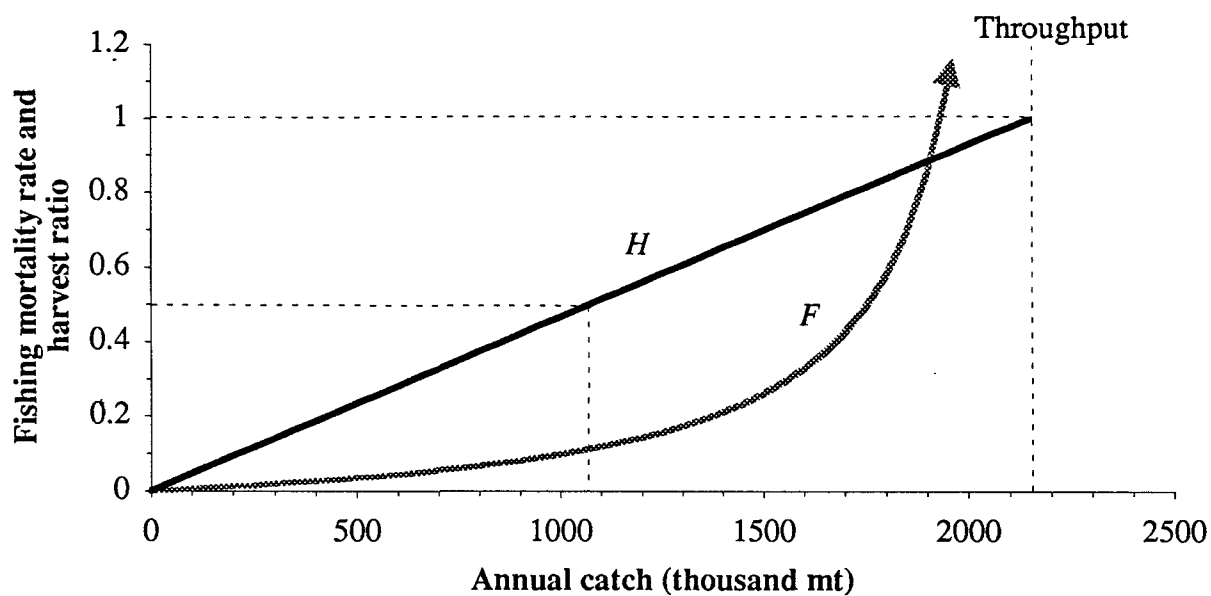


Figure 8. Predicted yellowfin harvest ratio as a function of annual catch. The bars represent 95% confidence intervals.

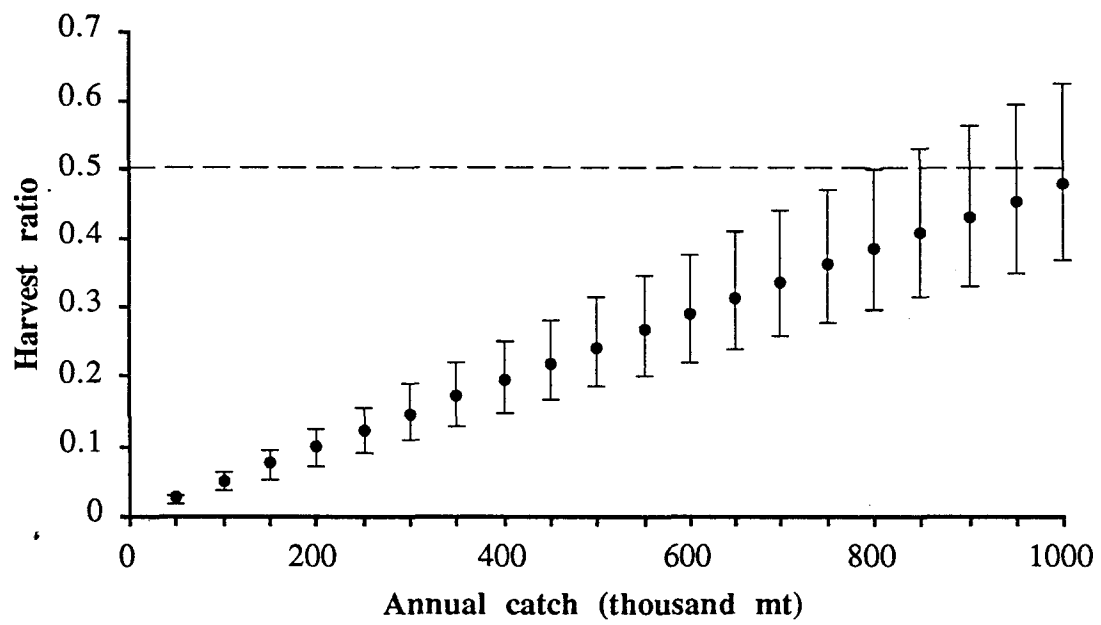
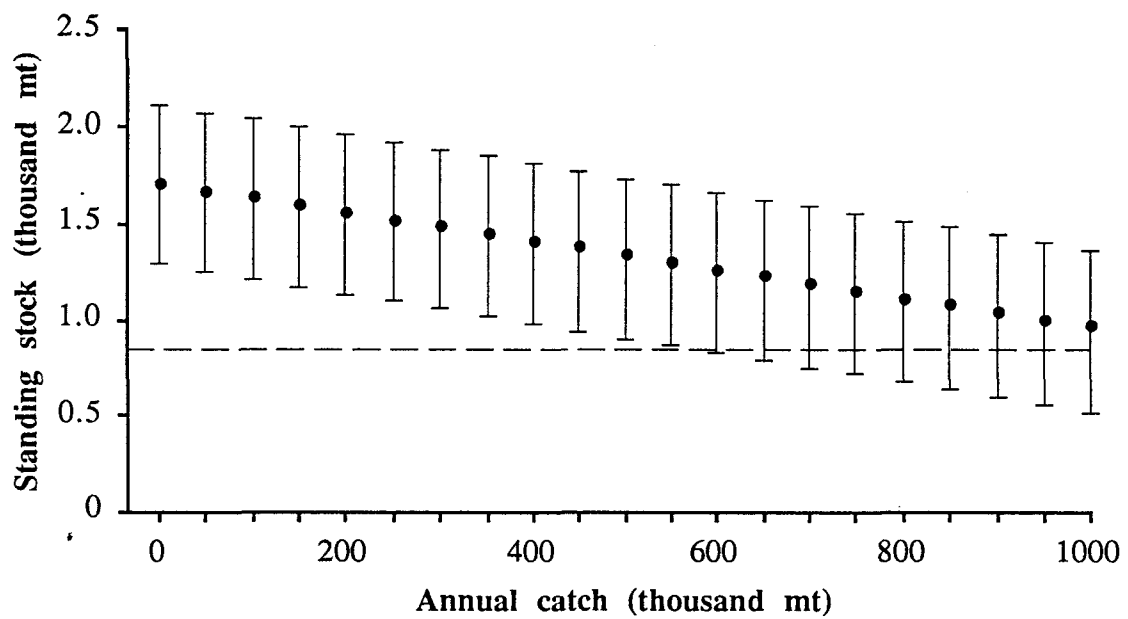


Figure 9. Predicted yellowfin standing stock as a function of annual catch. The bars represent 95% confidence intervals. The dashed line represents half the estimated unexploited standing stock.



APPENDIX

EFFECT OF SIZE STRUCTURE ON ATTRITION-MODEL ESTIMATES

The tag-attrition model (Hampton 1992), as currently formulated, takes no account of the size structures of the population, the catch, or the fish tagged. In a real fishery and experimental situation, each of these distributions is likely to differ. The objective of this note is to explore how these differences in size structure effect the estimates of parameters of the tag-attrition model and their subsequent interpretation about stock assessment. This is done using a size-structured simulation model.

Simulation Model

The simulation model is similar in concept to that used to estimate confidence intervals of parameters, i.e. the model simulates the fates of individual fish, with the survival and capture processes being driven by stochastic decision making. The model has the following features:

- (i) Recruitment is constant and occurs instantaneously at the beginning of every month. In these runs of the model, recruitment was set to 1,000 "units" per month. In terms of the model, these units are individual fish, however for ease of interpretation, we can define a "unit" to be any number of recruits we want, e.g. 1 unit = 100,000 recruits, making monthly recruitment 100,000,000. This was done to conserve processing time, which is proportional to the number of units.
- (ii) The size at recruitment was arbitrarily set at 30 cm, the length about which yellowfin begin to be caught in surface fisheries. Fish smaller than 30 cm were not considered by the model.
- (iii) The growth of individual fish was modelled using a von Bertalanffy growth equation, with individual variation in L_{∞} . The parameters used were $K = 0.5 \text{ yr}^{-1}$, mean $L_{\infty} = 180 \text{ cm}$ and s.d. $L_{\infty} = 18 \text{ cm}$. Individual values of L_{∞} were sampled from a normal distribution defined by this mean and s.d.
- (iv) Natural mortality was assumed constant across time periods and length intervals, and was set at 0.8 yr^{-1} . Full recruitment fishing mortality (F_r) was set at 0.4 yr^{-1} , with the actual fishing mortality for particular length classes determined by $F_l = F_r \cdot S_l$, where S_l are selectivity coefficients (for full recruitment, $S_l = 1$, for pre-recruitment, $S_l = 0$). These selectivity coefficients can be manipulated to obtain fisheries with various selective characteristics. Selection can take place at any size, not just at small sizes. In this sense, selection is a "whole population" parameter, and might be thought of as stock availability to the gear at different sizes.
- (v) Tagged fish were released independently to the fishery and the size distribution of tag releases was determined by a tagging probability schedule (t_l), constructed by size class, that is similar in concept to the S_l described above. In this case, a "full recruitment" tagging probability, T_r , is specified, and the number of fish tagged, by size class, is given by $N_l = P_l \cdot T_r \cdot t_l$, where P_l is the total population in size class l . This was done so that the sizes of tagged fish could be independent of the size composition of the catch, if necessary.

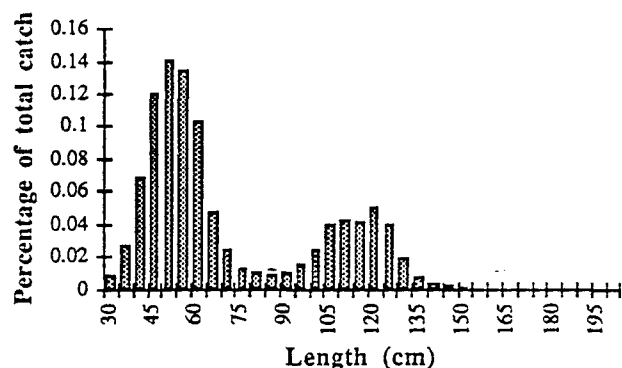
Simulation runs

The major questions addressed by this note are:

- (i) How does size selection in the fishery generating tag recaptures affect tag-attrition model parameter estimates?
- (ii) How does the size distribution of tag releases affect tag-attrition model parameter estimates?

Two categories of fishery were investigated in relation to question (i), a totally non-size-selective fishery (i.e. all $S_l = 1$) and a fishery that has size-selective characteristics similar to western Pacific yellowfin. In the latter case, the S_l were adjusted by trial and error so that a size composition similar to the bimodal 1990 purse seine yellowfin size composition (Figure A1) was obtained.

Figure A1. Length-frequency distribution of the 1990 purse seine catch of yellowfin in the western Pacific.



In relation to question (ii), four types of tagging experiment were simulated. In the first, the tagged fish were a random sample of the population larger than 30 cm. In the second, the tagged fish were a random sample of the catch. In the third, most of the tagged fish corresponded to the smaller mode of the catch. In the fourth, most of the tagged fish corresponded to the larger mode of the catch.

We therefore have seven unique simulation runs (not eight, because a tagging experiment in which the size distribution of releases is a random sample of the population and one in which the size distribution of releases is a random sample of the catch are identical if the catch is non-size-selective), shown below in Table A1.

Table A1. Characteristics of simulation runs.

Run number	Catch selectivity	Sizes of tag releases
1	No selectivity	Random sample of population
2	No selectivity	Small
3	No selectivity	Large
4	Selective	Random sample of population
5	Selective	Random sample of catch
6	Selective	Small
7	Selective	Large

The size compositions of the population, catch and tag releases for each run are shown in Figure A2.

Each simulation was allowed to run for 120 months. Tag releases were simulated during months 61-72, with recaptures being recorded throughout months 61-120. The first 60 months were disregarded as this period is required to allow the largest sizes to be represented in the population subjected to the tagging experiments.

Tags were aggregated by month of release and recapture, and total catch by month in weight was computed using the western Pacific length-weight relationship of Morita (1973). Such data from each of the seven simulations were analysed using the equilibrium tag-attrition model (model 1).

Figure A2. Length-frequency distributions of the population, catch and tag releases for the various simulation runs.

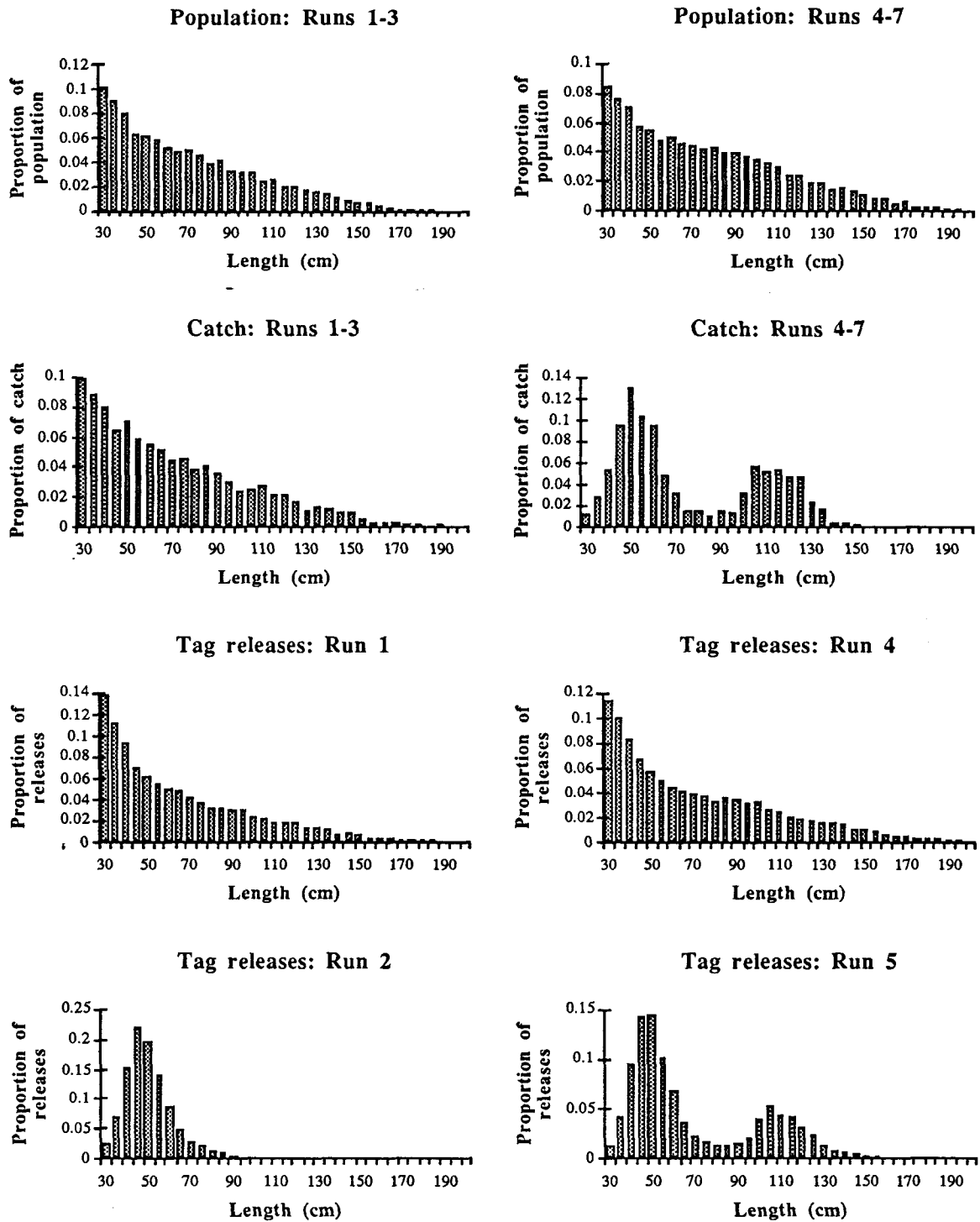
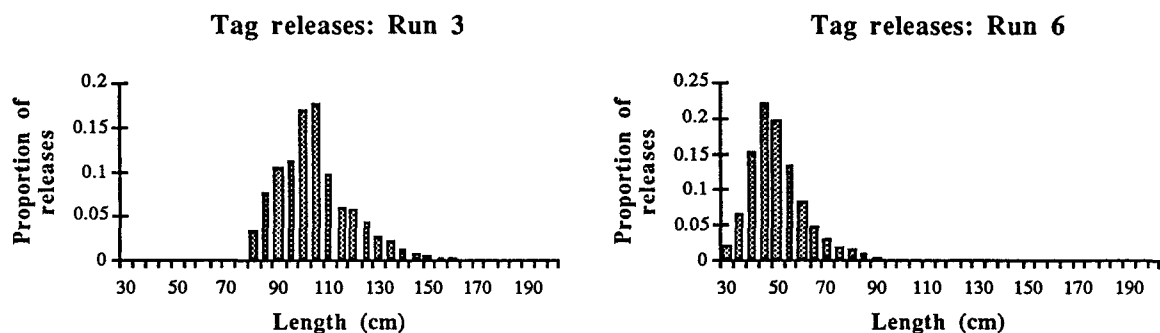


Figure A2. Continued.



To facilitate comparisons with the tag-attribution model parameter estimates, average total population size in weight, average total fishing mortality and average harvest ratio over months 61-120 were also computed. The average fishing mortality was found by averaging the individual monthly F_j 's found by solving the catch equation:

$$C_j = P_j \frac{F_j}{F_j + M} [1 - e^{-(F_j + M)}]$$

The average harvest ratio was in turn calculated by averaging:

$$H_j = \frac{F_j}{F_j + M}$$

Comparisons of true and estimated parameters for each simulation are shown in Table A2.

Table A2. Comparisons of true and estimated parameters.

Run No.	<i>M</i>			<i>P</i>			<i>F</i>			<i>H</i>		
	True	Est.	±%	True	Est.	±%	True	Est.	±%	True	Est.	±%
1	0.800	0.818	+2.2	126	119	-5.6	0.406	0.433	+6.6	0.337	0.335	-0.6
2	0.800	0.812	+1.50	126	124	-1.6	0.406	0.413	+1.7	0.337	0.337	0.0
3	0.800	0.782	-2.2	126	123	-2.4	0.406	0.418	+3.0	0.337	0.348	+3.3
4	0.800	1.051	+31.4	202	135	-33.2	0.146	0.222	+52.0	0.154	0.175	+13.6
5	0.800	1.087	+35.9	202	120	-40.6	0.146	0.251	+71.9	0.154	0.188	+22.0
6	0.800	0.931	+16.4	202	134	-33.7	0.146	0.223	+52.7	0.154	0.193	+25.3
7	0.800	1.463	+82.9	202	96	-52.5	0.146	0.319	+118.4	0.154	0.179	+16.2

Effect of Fishery Size Selection

The effects of fishery size selection can be seen by comparing runs 1-3 with runs 4-7. It is clear from such comparisons that size selection has a considerable effect on the tag-attribution model parameter estimates, or at least on their interpretation. Where there is no size selection, i.e. the catch size composition is identical to the population size composition, all parameters are accurately estimated. The slight differences shown in Table A2 for runs 1-3 are probably the result of the stochastic nature of the simulation model; if the simulations were repeated many times, the average parameter estimates should closely approach the true values input to the simulation model.

On the other hand, for a fishery showing size-selective characteristics similar to those of western Pacific yellowfin, the parameter estimates are biased -- M is over-estimated, P is under-estimated, F is over-estimated and H is over-estimated. The reasons for these biases appear to be fairly straight forward.

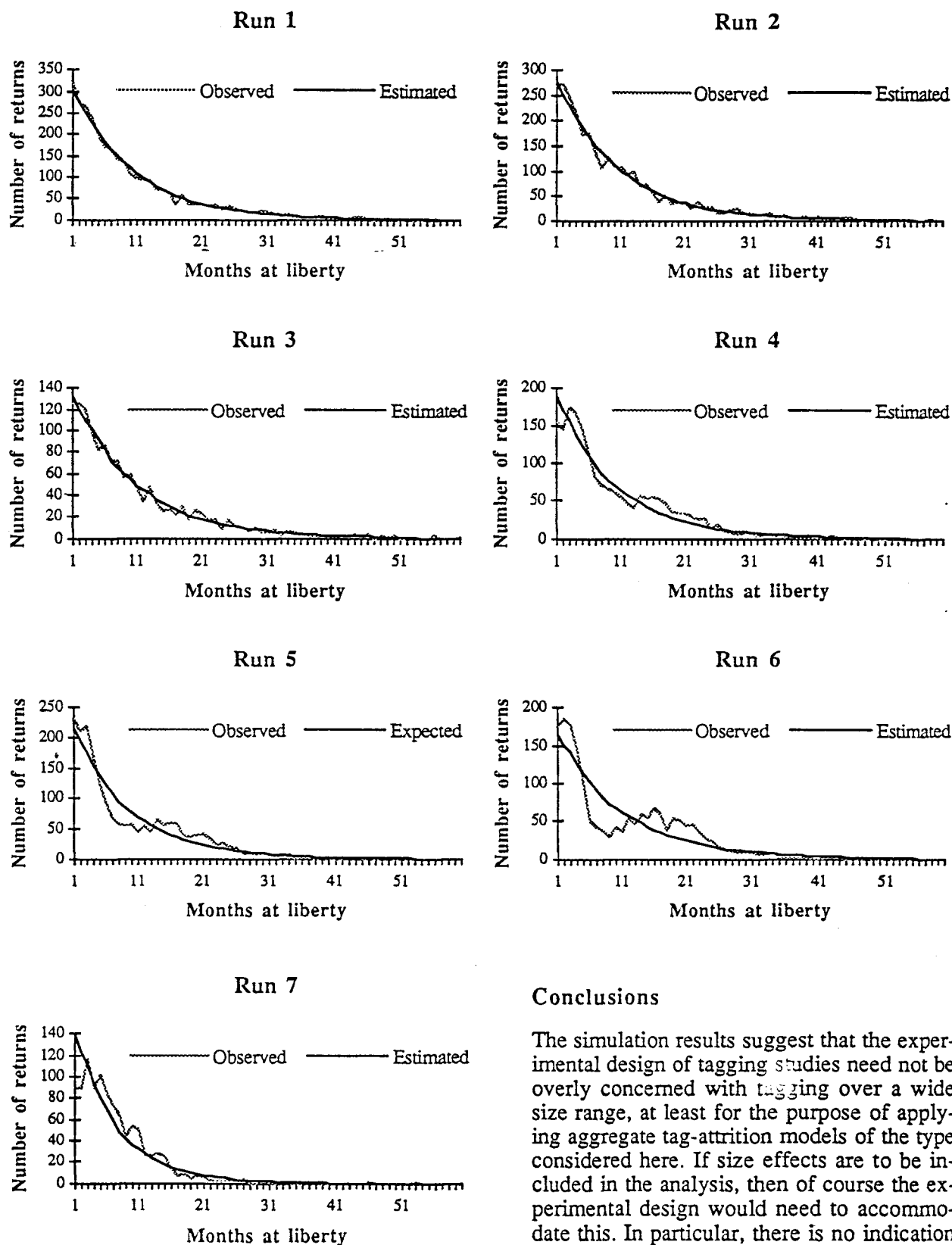
- First, the positively biased M estimates are likely to result from the model interpreting declining vulnerability of the population to the fishery on the right-hand sides of both length modes as tag attrition, the major component of which is natural mortality. Some indication of this can be seen from the plots of aggregate observed and estimated tag attrition (Figure A3). The observed pattern of tag recoveries are strongly influenced by the selective characteristics of the fishery recapturing the tags. However, the tag-attribution model knows nothing about selectivity, and therefore simply tries to find the best fit to the observed data. It appears to do this by increasing the natural mortality rate to compensate for the lower vulnerability of medium- and large-sized fish.
- Second, the tag-attribution model estimates parameters only for the portion of the population that it "sees", that which is vulnerable to the fishery. Hence, the population estimates for a size-selective fishery are considerable under-estimates of the total population because a substantial portion of that total population is not vulnerable to the fishery. This in turn results in over-estimates of fishing mortality and harvest ratio because these quantities are relative to the vulnerable portion of the population only.

It is also worth noting the effect that a size-selective fishery has on the interpretation of recruitment. In a size-structured population, recruitment is often thought of as occurring in a gradual fashion according to selectivity. This concept is less clear in the simulation runs 4-7, and presumably in the real yellowfin fishery, where vulnerability to the fishery appears to decline at medium sizes (hence the gap between the two modes in Figure A1) and a second recruitment "phase" occurs at larger size. In this case, it is easier to think of recruitment as occurring instantaneously at the smallest size, with its availability to the population being controlled through the selectivity schedule. Of course, the tag-attribution model knows none of this, and measures recruitment as an aggregate quantity over the entire length range. This quantity is therefore substantially higher than the instantaneous recruitment at 30 cm (about 12,000-14,000 biomass units per month for the total size range compared to 550 biomass units per month at 30 cm). This serves to illustrate that the turnover rates estimated by the tag-attribution model refer only to the *available* portion of the population, and must therefore be higher than the turnover rates that pertain to the whole population.

Effect of Size Distribution of Tag Releases

The tag-attribution model parameter estimates appear to be largely insensitive to the size distribution of tag releases. For the non-size-selective case (runs 1-3), accurate parameter estimates were obtained regardless of whether sizes at tag release were representative of the population and catch or were biased towards small or large fish. For the size-selective case (runs 4-7), no tagging strategy with respect to size at release could resolve the biases introduced by the size-selective nature of the fishery. Tagging a random sample of the population, a random sample of the catch or a sample comprising mostly small fish gave similar results in terms of bias in tag-attribution model parameter estimates. The magnitude of the biases was somewhat greater when only large fish were tagged.

Figure A3. Aggregate observed and estimated tag-attrition curves.



Conclusions

The simulation results suggest that the experimental design of tagging studies need not be overly concerned with tagging over a wide size range, at least for the purpose of applying aggregate tag-attrition models of the type considered here. If size effects are to be included in the analysis, then of course the experimental design would need to accommodate this. In particular, there is no indication that an experimental design in which mostly small fish are tagged introduces any extra

bias into attrition-model parameter estimates. In a size-selective fishery at least, it would appear that tagging mainly small fish is far preferable to tagging mainly large fish in this respect.

A far greater problem in terms of attrition-model parameter estimates is the effect of a size-selective recapture fishery. Apart from the over-estimates of M , this is largely a question of parameter interpretation, i.e. the estimates obtained are only pertinent to the vulnerable portion of the population. If good catch size-composition data are available, it might be possible to design an integrated analysis of tagging and length-frequency data that would correct the parameter estimates for size selectivity.

The simulations presented above are somewhat extreme in how they assume size-selectivity operates. While such selectivity almost certainly occurs in the western Pacific yellowfin fishery, it may not be as severe as that portrayed in the simulations. For example, the yellowfin aggregate tag-attrition curve (Figure 5, main text) does not show any evidence of an increasing recapture rate after about 12 months at liberty (cf Figure A3, run 6). It is possible that at least some of the bimodal structure of the catch size composition may be due to seasonality in recruitment.

In any case, it is useful to note that the biases in the parameter estimates, which might also be present to some extent in the analyses of real yellowfin tagging data, all lead to more pessimistic assessments of the stock, i.e. they result in higher F and H , and lower P . This means that if these biases are present in the analyses of real data, then the real stock condition might be even better than that indicated by the analyses to date. This is certainly not an unwelcome result.

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