Honolulu, Hawaii
June 17-24, 1992

WESTERN PACIFIC YELLOWFIN TUNA RESEARCH GROUP WORKSHOP

AND

SPC STANDING COMMITTEE ON TUNA AND BILLFISH PROGRAM MEETING

Doc. No. 6

NATURAL MORTALITY RATE OF PACIFIC YELLOWFIN TUNA: A REVIEW

by John Hampton

Tuna and Billfish Assessment Programme
South Pacific Commission
B.P. D5 Noumea, New Caledonia

Working paper for
Western Pacific Yellowfin Tuna Research Group Workshop
Honolulu, Hawaii
June 17-24, 1992

NOT TO BE CITED WITHOUT AUTHOR'S PERMISSION

NATURAL MORTALITY RATE OF PACIFIC YELLOWFIN TUNA: A REVIEW

by

John Hampton
Tuna and Billfish Assessment Programme
South Pacific Commission
B.P. D5 Noumea, New Caledonia

1. INTRODUCTION

With the exception of surplus production models, all fish population dynamics models that are routinely used for stock assessment require either that the instantaneous rate of natural mortality (*M*) be estimated from the data simultaneous with the other parameters of interest, or, more commonly, be independently estimated or assumed. A feature of fish stock analysis that appears to be fairly general is that the results of the analyses are rarely robust to either incorrectly assumed or poorly resolved values of *M*. However, because natural death is rarely directly observable in fish populations, *M* is notoriously difficult to estimate accurately. This dilemma has occupied fisheries biologists, mathematicians and statisticians for decades, and is at the heart of many of the problems of fish stock assessment.

In this paper, I review some of the existing methods for estimating *M* and their application to the Pacific yellowfin, *Thunnus albacares*, making the distinction between estimates for the eastern Pacific and western Pacific stocks where appropriate. The review draws heavily on the recent reviews, and the source material cited therein, of Wild (1991) for the eastern Pacific and Suzuki (1991) for the western Pacific.

2. METHODS FOR ESTIMATING *M*

Vetter (1988) classified methods for estimating *M* into (i) catch-analysis methods (including tag recapture), (ii) life history methods and (iii) predation methods. Of these, predation methods would appear to have the least potential for yellowfin tuna. This is because information on the population dynamics of the possible predators of yellowfin (presumably large billfish, sharks and other large tuna, including yellowfin itself) that is required to implement these methods is lacking. Also, at least for much of the exploited phase of its life history, yellowfin probably suffer minor predation mortality relative to other mortality sources, such as starvation, environmental stress and senescence. Predation methods are therefore not considered further in this review. The remaining methods are briefly described and classified in a similar way to that of Vetter (1988).

2.1 Catch-Curve Analysis

Catch-curve analysis involves the assemblage of catch-at-age data for a cohort and the fitting of a straight line to the descending limb of the logged catches (Figure 1), where the slope of the fitted line is an estimate of $-Z$ ($Z=M+F$). In order to estimate *M*, the catch samples must be taken from a stock that is lightly exploited, i.e. where $F=0$ and $M=Z$ is a reasonable assumption. If *F* is in fact significant, a series of catch curves can be constructed at different stages of the development of the fishery, and the resulting *Z* estimates regressed against fishing effort (or some average effort for that cohort) (Figure 2). The resulting fitted line has a slope of *q* (catchability coefficient) and an intercept of *M* (i.e. *Z* at zero effort).

Figure 1. Catch curve analysis

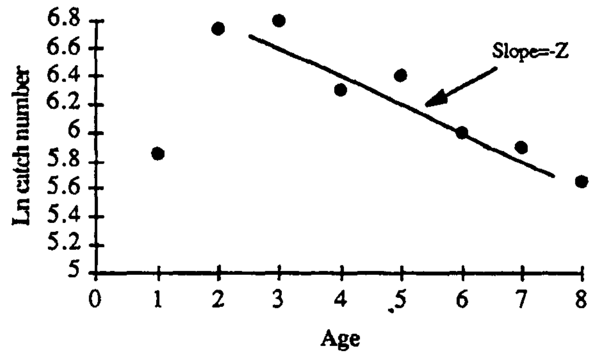
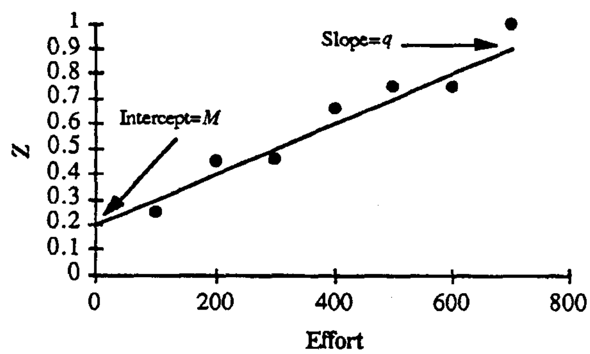


Figure 2. Regression of Z on effort.



These very simplistic methods are associated with numerous assumptions (listed in some detail by Vetter 1988), many of which rarely hold for most fisheries data sets. Two assumptions that are particularly troublesome for tuna fisheries are accurate measurement of fishing effort and constant catchability for different ages and levels of effort.

2.2 Integrated Stock Analysis Models

Some of the difficulties of catch-curve analysis are dealt with in more complex catch-analysis models, where at least some of the restrictive assumptions are relaxed by the incorporation of extra model structure (i.e. parameters) and data. These models, most of which were reviewed by Megrey (1989), have the capacity, at least in theory, to estimate M simultaneously with other parameters of interest, such as q, population abundances, availability and gear selectivity parameters. An extension of one of these models (Fournier and Archibald 1982), using the MULTIFAN method of estimating age composition from size composition (Fournier *et al.* 1990), is currently under development for South Pacific albacore and might also be suitable for application to western Pacific yellowfin.

The use of integrated stock analysis models has some attractive features not available to sequential methods of stock analysis. Foremost is that the error structure in the data is preserved through all analytical "steps", and more realistic confidence intervals on parameter estimates will result. However, in reality, it is unlikely that these models will be able to resolve all parameters of interest from fishery data alone. For example, a common problem is a high negative correlation between M and q, thus resulting in a poor separation of Z into its M and F components (Megrey 1988). The way around problems such as this is to give the model more information to work with in the form of ancillary data sets. The types of ancillary data that might be included for the MULTIFAN-based model mentioned above are catch-at-age and/or length-increment data to help resolve age composition estimates, tag-return data to help resolve mortality estimation and separation, and abundance index data to help resolve time-series trends in abundance.

2.3 Tag-Recapture Methods

As Vetter (1988) concludes, "Careful, repeated tagging experiments probably hold the most promise for determining with any reasonable degree of accuracy, rates of natural mortality in fish stocks". The equations that are applied to tagging data for the estimation of mortality rates are essentially the same as those that are typically used for stock assessments based on catch-at-age data (in particular the Baranov 1918 catch equation). The equations are constructed to give predictions of tag returns by time period, conditional on some set of model parameters, which typically include M and F (by time period), although F is usually re-parameterized as a function of catch or effort by the recapture fishery. The model parameters are varied by a nonlinear optimization routine in an attempt to find the parameter set that results in the best match of predicted and observed tag returns (according to some statistical criterion, such as maximum likelihood). Examples of the application of these types of models to estimation of tuna mortality rates include Kleiber *et al.* (1987) for western Pacific skipjack and Hampton (1991) for southern bluefin tuna.

Tag-recapture methods will not necessarily provide unequivicol results with respect to M or other parameter estimates. Of particular importance is the need to account for all sources of tag loss from the experimental population. Unless independent estimates are available, M will be totally confounded with other type-2 (long-term) tag loss rates, such as type-2 tag shedding, type-2 tagging mortality, permanent emigration from the area of the fishery and growth out of the vulnerable size classes, if they are present. Type-1 sources of tag loss, such as immediate tag shedding, immediate tagging mortality and non-reporting, affect the partitioning of Z into its M and F components (but not necessarily the estimate of Z itself) and must also be accounted for. Various techniques, which are described in detail in SCTB 5/WP.3, can be employed to either minimize or estimate these effects.

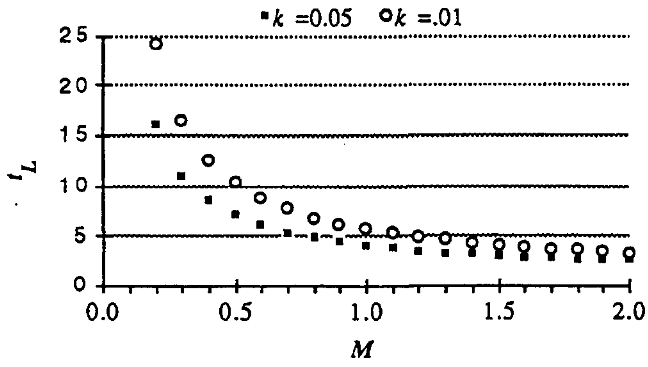
2.4 Life History Methods

Various authors (e.g. Pauly 1980, Hoenig 1983 and others cited in Vetter 1988) have drawn attention to the fact that M (or Z) is strongly correlated with various life history parameters, such as growth rate, longevity, age at sexual maturity, etc., thus enabling predictions of M (or Z) to be made on the basis of such relationships. These relationships may take an analytical form or an empirical form (with or without a theoretical basis). Without reviewing the variety of techniques that have been applied (see Vetter 1988 for more details), I shall outline one such technique that may be useful to derive a first estimate of M for yellowfin, or at least to provide a point of comparison with other estimates. The method basically involves the following analytical formula modified from Hoenig (1983):

$$Z = -\frac{\ln(k)}{(t_L - t_R)}$$

where t_L is the age to which an arbitrarily small proportion, k, of recruits survive from an initial age at recruitment, t_R. If an estimate of t_L can be obtained for a period when the stock was unexploited, or only lightly so, then M (=Z) can be estimated. Plots of t_L against M for two values of k for hypothetical unexploited populations are shown in Figure 3. The age at which only small numbers (5% or 1%) of the population, originally alive at age t_R=1 yr, remain declines exponentially with increasing M. The longest ever period at liberty for a yellowfin tagged in the western Pacific is 7 years (Itano and Williams 1992); this fish was 34 cm (approximately 0.5 years of age) at release. As most of the catch of yellowfin is estimated to be less that 6 years of age (Suzuki *et al.* 1989), we might assume that the age of this tagged yellowfin is indeed a rare event and should, for the purpose of this exercise, represent an upper quantile of the maximum age expectancy of the order of those used in Figure 3. Under this assumption, an estimate of M (yellowfin were relatively lightly exploited during the early 1980's when the tagged fish was at large) would be of the order 0.5-0.9 yr^{-1}.

Figure 3. Relationship between longevity (t_L) and M for unexploited populations.



3. ESTIMATES OF M

Previous estimates of M have been summarized by Cole (1980) for the Pacific, Suzuki (1991) for the western Pacific and Wild (1991) for the eastern Pacific. These estimates, and associated information, are compiled in Table 1. Most of the older estimates are based on catch curve analyses, presumably after the conversion of size composition to age composition using a von Bertalanffy growth equation. These estimates would therefore be sensitive to the growth parameters used; the effects of incorrect growth parameters would be particularly strong for estimates involving older fish (estimates 2, 4). Also, several of these estimates are from restricted areas relative to the overall stock distribution (assuming separate western/central and eastern stocks) and therefore would contain significant components of emigration out of the area being considered (estimates 5, 6).

The estimates based on life history parameters (estimates 7, 8, 9) must be considered as very approximate, particularly those based on empirical relationships incorporating observations from diverse groups of fish and invertebrates (estimates 7, 8).

The estimate for the western Pacific based on recent analyses of tag-recapture data (estimate 10) is preliminary at this stage, but it is worth noting that it was the best determined of the population parameters estimated in that particular analysis. The estimate (1.07 yr^{-1}, with 95% confidence intervals of 0.92-1.22 yr^{-1}) has been corrected for all other sources of tag loss except permanent emigration from the study area considered. Given the size of the area and the few observations of tag recoveries from outside it, it is argued in SCTB 5/WP.3 that this source of tag loss is probably minor.

4. FUTURE STUDIES

Through the size composition, catch and effort data now being compiled by this working group and the large amount of tag-recapture data rapidly accumulating to SPC's Regional Tuna Tagging Project (RTTP), the stage is now set for more accurate estimates of M and other population parameters to be obtained. These two primary data sets would appear to define two related avenues of investigation:

(i) Further analyses of the tag-recapture data, with supporting catch data, will update and refine the preliminary estimate of M given in SCTB 5/WP.3. Various additional structure could be incorporated into the models developed for this preliminary analysis, including:

- size or age structure
- alternative functional forms of M (i.e. allowing M to vary with age or size)
- spatial structure

Table 1. Existing estimates of *M* for Pacific yellowfin.

	M estimate[1]	Method	Age range	Region	Source
1.	0.34	Catch curve (sequential recruitment)	1-3 yr	Western and central Pacific	Ishii (1967a,b,1968,1969) (after Cole 1990)
2.	0.91	Catch curve (sequential recruitment)	>4 yr	Western and central Pacific	Ishii (1967a,b,1968,1969) (after Cole 1990)
3.	0.3 or 0.9	Catch curve	2-3 yr	Western and central Pacific	Honma *et. al.* (1971) (after Cole 1990)
4.	1.2	Catch curve	>4 yr	Western and central Pacific	Honma *et. al.* (1971) (after Cole 1990)
5.	2.5	Catch curve	>2 yr	Western Pacific	Honma *et. al.* (1971) (after Suzuki 1991)
6.	1.1	Catch curve	>2 yr	Central Pacific	Honma *et. al.* (1971) (after Suzuki 1991)
7.	0.3	Life history	n.a.	Western and central Pacific	Honma *et. al.* (1971) (after Suzuki 1991)
8.	0.5	Life history	n.a.	Philippines	White (1982) (after Suzuki 1991)
9.	0.6-0.9	Life history	n.a.	Western Pacific	This paper
10.	1.07 (0.92-1.22)[2]	Tag recapture	0.5-2 yr	Western Pacific	SCTB 5/WP.3
11.	0.77 (0.64-0.90)[2]	Catch curve	1-3 yr	Eastern Pacific	Hennemuth (1961) (after Cole 1990)
12.	0.55-1.05	Catch curve	1-3 yr	Eastern Pacific	Schaefer (1967) (after Cole 1990)
13.	<2.0	Tag recapture	1-3 yr	Eastern Pacific	Bayliff (1971) (after Cole 1990)
14.	0.6	Simulation	1-3 yr	Eastern Pacific	Francis (1977) (after Cole 1990)

[1] All estimates are given in units of yr^{-1}.
[2] 95% confidence interval.

This tag data set probably has the most potential, in the short term, for obtaining new information about *M* and its variability.

(ii) The compilation of an effort and catch-at-size data base creates the opportunity to develop an integrated stock analysis model for yellowfin, as described briefly in section 2, that may simultaneously provide estimates of *M* and other population and fishery parameters of interest. The first step in this process would be to assess the newly compiled size composition data for its suitability for analysis by a MULTIFAN type model. (As noted earlier, the software is currently being developed for South Pacific albacore, and may be easily modified for yellowfin analyses.) The simultaneous analysis of tagging and length-age data (which will be assembled from otolith samples taken during the RTTP) may need to be considered as it is unlikely that all parameters of interest (including *M*) will be estimable from the catch-at-size and effort data alone.

When we speak of integrated stock analysis models, the analyses of tagging data (with supporting catch, effort or size composition data) and the analyses of catch-at-size data (with supporting effort, tagging and length-age data) in fact begin to merge. It is the firm view of the author that the integrated stock analysis model, rather than the traditional sequential style of "cohort analysis" and its variants, is what we should now be striving for.

REFERENCES

Baranov, T.I.

1918 On the question of the biological basis of fisheries. Nauchn. Issled. Ikhtiol. Inst. Izv. 1:81-128 [in Russ.].

Bayliff, W.H.

1971 Estimates of the rates of mortality of yellowfin tuna in the eastern Pacific Ocean derived from tagging experiments. Inter-Amer. Trop. Tuna Comm., Bull., 15:379-436.

Cole, J.S.

1980 Synopsis of biological data on the yellowfin tuna, *Thunnus albacares* (Bonnaterre, 1788), in the Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Spec. Rep., 2:71-150.

Fournier, D.A., and C.P. Archibald.

1982 A general theory for analysing catch at age data. Can. J. Fish. Aquat. Sci. 39:1195-1207.

Fournier, D.A., J.R. Sibert, J. Majkowski, and J. Hampton.

1990 MULTIFAN a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Can. J. Fish. Aquat. Sci. 47:301-317.

Francis, R.C.

1977 TUNPOP: a simulation of the dynamics and structure of the yellowfin tuna stock and surface fishery of the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Bull., 17(4):233-279.

Hampton, J.

1991 Estimation of southern bluefin tuna *Thunnus maccoyii* natural mortality and movement rates from tagging experiments. Fish. Bull., U.S. 89:591-610.

Hennemuth, R.C.

1961 Year class abundance, mortality and yield-per-recruit of yellowfin in the eastern Pacific Ocean, 1954-1959. Inter-Amer. Trop. Tuna Comm., Bull., 6:1-51.

Hoenig, J.

1983 Empirical use of longevity data to estimate mortality rates. Fish. Bull., U.S. 82:898-903.

Honma, M., T. Kamimura, and S. Hayasi.

1971 Compilation of catch records for assessment of yellowfin tuna stocks in longline fishery in the Pacific Ocean, and application to data for the years of 1950 to 1965. Far Seas Fish. Res. Lab., Bull., 4:1-26.

Ishii, T.

1967a Studies on estimating parameters of a fish population supplied by sequential recruitment - I. The effect on estimates for Pacific yellowfin tuna. Jap. Soc. Sci. Fish., Bull., 33(6):513-523.

Ishii, T.

1967b Studies on estimating parameters of a fish population supplied by sequential recruitment - II.

A method of simultaneous estimation by minimizing the tracing index. Jap. Soc. Sci. Fish., Bull., 33(8):738-745.

Ishii, T.

1968 On population parameters of yellowfin and bigeye tunas in the Pacific. Japanese Tuna Conference in Shimizu (Showa 42 nendo), Proc., 72-76.

Ishii, T.

1969 Studies on estimating parameters of a fish population supplied by sequential recruitment - V. Simultaneous estimation of parameters with the transfer effect of Pacific yellowfin tuna. Jap. Soc. Sci. Fish., Bull., 35(6):537-545.

Itano, D.G., and P.G. Williams.

1992 Preliminary analysis of yellowfin tagging data and related information collected by the Skipjack Survey and Assessment Programme. South Pac. Comm. Tuna and Billfish Assess. Prog. Tech. Rep. No. 28. (In prep.)

Kleiber, P., A.W. Argue, and R.E. Kearney

1987 Assessment of Pacific skipjack tuna (*Katsuwonus pelamis*) resources by estimating standing stock and components of population turnover from tagging data. Can. J. Fish. Aquat. Sci. 44:1122-1134.

Megrey, B. A.

1989 Review and comparison of age-structured stock assessment models from theoretical and applied points of view, p. 8-48 *In* E. F. Edwards and B. A. Megrey (eds) Mathematical analysis of fish stock dynamics. American Fisheries Society Symposium 6, Bethesda, Maryland.

Pauly, D.

1980 On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. Int. Explor. Mer 39(2):175-192.

Schaefer, M.B.

1967 Fishery dynamics and present status of the yellowfin tuna population of the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Bull., 12(3):87-136.

Suzuki, Z.

1991 A review of biology and fisheries for yellowfin tuna *Thunnus albacares* in the western and central Pacific Oceans. TIC/91/BP#6, FAO Expert Consultation on Interactions of Pacific Tuna Fisheries, Noumea, New Caledonia, 3-11 December 1991.

Suzuki, Z., N. Miyabe and S. Tsuji.

1989 Preliminary analysis of fisheries and some inference on stock status for yellowfin tuna in the western Pacific. Paper presented to the Second Standing Committee on Tuna and Billfish, Suva, Fiji, June 1989.

Vetter, E.F.

1988 Estimation of natural mortality in fish stocks: a review. Fish. Bull., U.S. 86:25-43.

White, T.F.

1982 The Philippines tuna fishery and aspects of the population dynamics of tunas in Philippine waters. Indo-Pacific Tuna Dev. Manag. Prog., IPTP/82/WP/5.

Wild, A.

1991 A review of yellowfin tuna biology and fisheries in the eastern Pacific Ocean. TIC/91/BP#5, FAO Expert Consultation on Interactions of Pacific Tuna Fisheries, Noumea, New Caledonia, 3-11 December 1991.