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EFFECTS OF FISHING MODES ON ESTIMATES OF FISHING POWER, RELATIVE ABUNDANCE AND SURPLUS PRODUCTION IN THE EASTERN PACIFIC YELLOWFIN TUNA FISHERY

by

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INTRODUCTION

In terms of predominant modes of fishing, the fishery for yellowfin tuna in the eastern Pacific Ocean can be characterized by a three-stage historical development.

Firstly, from 1915 through 1958 live bait (or pole-and-line) fishing predominated. This method involves the capture of large quantities of live bait, such as sardines or anchovies, which in turn is used to attract and capture the tuna. During the baitboat era the tuna fleet ranged from Baja California to northern Chile. Due to limitations on the vulnerability of offshore tuna to bait fishing, with the exception of the vicinity of a few islands such as the Galapagos and the Revillagigedo, fishing was confined to within a few hundred miles of the coastline.

Secondly, between 1959 and 1961 the fleet was rapidly converted to purse-seining. Two reasons for this mass conversion in mode of fishing stand out:

1) the baitboat fleet was in rather poor economic condition due to competition from longline vessels which were able to undersell the surface-fishing vessels on the American market;
2) purse-seining techniques for tropical tunas were substantially improved due to the advent of commercially available nylon netting, the development of hydraulic net hauling gear (power blocks) and improved fish-carrying facilities.

These conversions resulted in significant increases in the efficiency of capture of tropical tunas by the surface fleet. By the end of 1961 the purse-seine vessels had extended their operations throughout the historic baitboat grounds (Figure 1, A1) and accounted for more than 85% of the tuna landed.

Thirdly, from 1962 until the present, as the capacity of the surface fleet increased the competition for fish intensified. As a consequence better techniques for purse-seining in offshore areas of the eastern Pacific were gradually developed. In order to operate in these high-seas areas, vessels had to be able to fish in more adverse conditions than previously, and the fleet had to develop techniques for harvesting tuna (predominantly yellowfin) which aggregated under schools of porpoise. In this method of fishing a pod of porpoise is located on the surface of the ocean. If it is determined that tuna are associating with them, speedboats are used to head the porpoise (and the tuna with them) into the optimum position for setting the net. After the net is set around both the porpoise and the tuna, the porpoise are released from the net and the tuna are loaded aboard the vessel. By 1964 the fleet was operating regularly at least 150 miles further offshore than in previous years. By the end of 1968 the fleet occupied an area nearly twice as large as the historic baitboat grounds, and by 1969 the area of operation reached beyond the western boundary of the Commission Yellowfin Regulatory Area (CYRA, Figure 2).

The modern purse-seine fishery involves two distinct types of schools, "porpoise fish" and "school fish", fished by two different modes. Porpoise fishing was described in the preceding paragraph. School fish (or non-porpoise) fishing involves location of fish on or near the surface of the ocean. Sometimes they are moving schools (breezers, jumpers, etc.) and sometimes the fish are found milling below floating objects such as logs or dead whales. These two modes of fishing are quite distinct in terms of vessel operation.

Porpoise and non-porpoise fishing in the eastern Pacific can be categorized in terms of areas where they take place and the sizes of fish which predominate in them. One can characterize these two modes of fishing in the following way:

1) The non-porpoise fishery exists primarily in the historical inshore area of the CYRA, roughly corresponding to Area A1 in Figure 1. About 85 percent of yellowfin taken in this fishery are less than 85 cm (approx. 25 lb., 12 kg.) in length.
2) The porpoise fishery is conducted both inshore and offshore, (Area A2 in Figure 1) mostly between 5°N and 15°N latitudes. About 70 percent of the yellowfin taken in this fishery are greater than 85 cm.

Finally, it appears that whereas in most years significant numbers of yellowfin are caught within the CYRA by porpoise fishing, only in certain years are large numbers of yellowfin caught by non-porpoise fishing. In other words small yellowfin are not available to the fishery in surface schools along the coastline every year. As an example, in 1972, a year that might be considered to be a "porpoise year", only 35% of the non-regulated yellowfin catch in numbers was taken by non-porpoise fishing, whereas in 1973, a year in which there was a large "run" of small (50-70 cm) yellowfin taken off the coast of southern Central America, approximately 80% of the non-regulated yellowfin catch in numbers was taken by non-porpoise fishing.

It is the general objective of this background paper to demonstrate that a comprehensive analysis of the recent eastern Pacific yellowfin purse-seine fishery should take these two modes of operation into account, or misleading results could arise. In particular, I wish to first examine the effects of modes of fishing on estimates of fishing power and relative yellowfin abundance within the CYRA. Secondly, with the aid of a computer simulation model of the CYRA yellowfin population structure and purse-seine fishery, I wish to look at the effects of the evolution of modal fishing on the standard estimates of yellowfin production within the CYRA.

FISHING POWER AND RELATIVE ABUNDANCE

In order to perform certain analytic procedures on fishery catch and effort data in cases where the effectiveness of various types or classes of effort differ when those classes are fishing simultaneously in time and space, the effort must first be standardized before it can be used in a subsequent analysis with the concomitant catch data.

For this analysis the non-regulated logged catch in weight and effort information for the years 1970 through 1974 was summarized as follows:

1) mode of fishing - porpoise, non-porpoise;
2) time - quarter of the year (Q1, Q2);
3) area - inshore (A1, A3, A4, A5), offshore (A40, A50)-Figure 3;
4) vessel size-class - SC1 (<600 ton carrying capacity), SC2 ($\geq$600 tons carrying capacity).

Quarters instead of months were used as time units to simplify the model. The areal stratification was an attempt to represent distinct subareas within the inshore and offshore fisheries. The boundaries coincided, wherever possible, with the Commission length-frequency (market-measurement) area boundaries. (Figure 4). For example, A1 encompasses a fairly distinct fishery which occurs off the coast of Baja California, in and around the mouth of the Gulf of California and around the Revillagigedo Islands. It was decided to partition the fleet into only two size classes based upon carrying capacity. The division of 600 tons was motivated by an earlier unpublished study by Tomlinson (personal communication). He found that in recent years substantial differences in fishing power occurred between vessels of these two size groups and that relatively small differences in fishing power occurred among subgroups (based upon carrying capacity) within the two size groups.

The basic analytic model used to estimate fishing power and relative stock abundance was first developed by Robson (1967) and is discussed for tuna fisheries by Joseph and Calkins (1969). The model evolves as follows from the general catch equation.

$$C_{ij} = q_i \, f_{ij} \, \bar{N}_j \, \varepsilon_{ij} \qquad (1)$$

where

C_{ij} = catch by a vessel of size class i fishing in time-area stratum j,

q_i = catchability coefficient for a vessel of size class i,

f_{ij} = fishing effort by vessels of size-class i in time-area stratum j,

$\bar{N}_j$ = mean population abundance in time-area stratrum j, and

ε_{ij} = lognormal random variable

The model (1) can be transformed into a general linear model as follows:

$$Y_{ij} = \alpha_i + \beta_j + \eta_{ij} \qquad (2)$$

where

$Y_{ij} = \ln \dfrac{C_{ij}}{f_{ij}}$,

$\alpha_i = \ln (q_i)$,

$\beta_j = \ln (\bar{N}_j)$, and

$\eta_{ij} = \ln (\varepsilon_{ij})$ and is a $N(0, \sigma^2)$ random variable.

Unfortunately, the parameters of the linear model (2) are not estimable since the design matrix has less than full rank. However, it can be reparameterized into an estimable form as follows.

Let

$\bar{\alpha} = \dfrac{1}{I} \sum_{i=1}^{I} \alpha_i$,

I = number of vessel size classes,

$\bar{\beta} = \dfrac{1}{J} \sum_{j=1}^{J} \beta_j$, and

J = number of time - area strata.

Then

$$Y_{ij} = (\alpha_i - \bar{\alpha}) + \bar{\alpha} + (\beta_j - \bar{\beta}) + \bar{\beta} + \eta_{ij} \qquad (3)$$

If we let

$\alpha'_i = \alpha_i - \bar{\alpha}$ and

$\beta'_j = \beta_j - \bar{\beta}$

The model (3) becomes

(4) $$Y_{ij} = \mu + \alpha'_i + \beta'_j + \eta_{ij}$$

where

$$\sum_{i=1}^{I} \alpha'_i = \sum_{j=1}^{J} \beta'_j = 0 \text{ and}$$

$$\eta_{ij} \sim N\ (o,\sigma^2).$$

which is an estimable form of the general linear model. The relative fishing power of a size class i relative to a standard size class s can now be estimated

(5) $$\hat{\rho}_i = \frac{\hat{q}_i}{\hat{q}_s} = e^{\hat{\alpha}'_i - \hat{\alpha}'_s}$$

In addition, the abundance of the underlying population in time-area stratum j relative to that in some other time-area stratum k can be estimated as follows:

(6) $$\frac{\hat{N}_j}{\hat{N}_k} = e^{\hat{\beta}'_j - \hat{\beta}'_k}$$

Two sets of analyses were performed on the summarized data. Firstly, the total (porpoise + non-porpoise), porpoise only and non-porpoise only sets of summarized catch-effort data were separately subjected to analysis of variance to determine whether the total catch and effort data demonstrated a consistent pattern of relative fishing power over the years 1970 through 1974 and, if not, whether any inconsistences in fishing power over time might be due to changes in the modal composition in the fishery. This was done because it is essential that estimates of fishing power account for all vessel size-class oriented variability in catch rates in order for those catch rates to be used to estimate relative atock abundance. If this were not the case for a particular set of catch rates, significant interactions between vessel size-class and time-area strata would be present. As a result, subsequent indices of abundance would be dependent upon the standard vessel size-class used. It should be noted here that not only was the catch separated into modes but the effort was also separated concommittantly. Thus the catch rates used in the modal analyses are catch rates while operating exclusively in one particular mode. Each of the three sets of data were subjected to the following analysis of variance model:

$$Y_{ijkl} = \mu + a_i + b_j + c_k + d_\ell + ab_{ij} + ac_{ik} + ad_{il} + bc_{jk} + bd_{jl} + cd_{kl} + \varepsilon_{ijkl}\ .$$

Y_{ijkl} = natural logarithm of the catch per unit of effort for year i area j, quarter k and size-class 1,

μ = overall mean log catch per unit of effort,

a_i = deviation from the mean due to year i,

b_j = " " " " " " area j,

c_k = " " " " " " quarter k,

d_ℓ = " " " " " " size-class ℓ

ab_{ij} = deviation from the mean due to interaction between year i and area j,

ac_{ik} = deviation from the mean due to interaction between year i and quarter k,

ad_{il} = deviation from the mean due to interaction between year i and size-class ℓ

bc_{jk} = deviation from the mean due to interaction between areas j and quarter k,

$bd_{j\ell}$ = deviation from the mean due to interaction between area j and size-class ℓ,

$cd_{k\ell}$ = deviation from the mean due to interaction between quarter k, and size-class ℓ and

ε_{ijkl} = N $(0,\sigma^2)$ random variable.

All six areas were used for both the total and porpoise analyses. Only the four inshore areas (A1, A3, A4, and A5) were used for the non-porpoise analysis since an insignificant number of non-porpoise fish were caught in the two outside areas (A40, A50) during those years. Separate analyses were performed for the inshore areas, the offshore areas and the total CYRA (combined inshore and offshore areas) for both the total and porpoise sets of data.

The results are presented in Table 1. Since it is hoped that these data can be used to estimate relative abundance of yellowfin one would wish to use sets of data where relative fishing power was relatively consistent over the time span. In this particular case I am interested in obtaining annual estimates of relative abundance for as large a subset of the CYRA as is possible. Thus it is of importance to examine the year x vessel size-class (YV) factor for its significance as a criterion for selecting appropriate data sets. It is quite obvious from Table 1 that fishing power varies significantly over time when the entire CYRA is being examined, regardless of whether the two fishing modes are separated or not. Since fishing power appears to be quite consistent over time within the non-porpoise fishery (which exists in the inshore area) and within the inshore and offshore porpoise fisheries, one would surmise that the apparent differences in fishing power are due to differences between the inshore and offshore porpoise fisheries. After examining the catch-effort and length-frequency data in detail and after having experienced the purse-seine fishery on a first-hand basis, several causes for these discrepancies in fishing power become apparent.

1) A significant amount of porpoise fishing takes place in the inshore areas at times when the fleet is concentrated in relatively small regions of high school-fish abundance (for example off the coast of Panama in 1973 and Costa Rica in 1974.) And, the methods of porpoise fishing under these conditions are significantly different from those employed in the offshore areas and in the inshore areas at times of low school-fish abundance. Since high school-fish abundance tends to draw large number of size-class 2 vessels away from the more traditional offshore porpoise areas into heavy concentrations in the inshore areas, significant changes in relative fishing power could result in the inshore porpoise fishery during these times. One could hypothesize that high concentrations of effort in relatively small areas would tend to eliminate the advantage that large boats have over small boats due to greater speed.

2) The species composition of porpoise is different between the inshore and offshore areas. Inshore, significant catches of yellowfin associated with white bellied porpoise (*Delphinus delphis*) are made, whereas offshore yellowfin are caught almost exclusively in conjunction with spotted (*Stenella graffmani*) and spinner (*S. longirostris*) porpoise.

Robson estimates of fishing power of size-class 2 relative to size-class 1 are given in Table 2. For both the total (porpoise + non-porpoise) and porpoise data, separate estimates were made for the inshore areas alone, offshore areas alone, and the total CYRA. Only the four inshore areas were used for the estimates of non-porpoise fishing power. However, separate estimates were made using the yellowfin catch only and the combined yellowfin-skipjack catch in the non-porpoise case, since most skipjack are caught inshore in association with surface schools of yellowfin. Several things are of interest to note.

Firstly, the estimates of relative fishing power for the two modes combined (Total) appear to lie between the estimates for porpoise only and non-porpoise only, particularly in the inshore area where both modes of fishing are practiced. Table 3 gives total non-regulated logged catch divided by total non-regulated logged effort for the two size-classes as well as their ratios (a rough index of fishing power) for the two modes combined (P + NP), porpoise only (P) and non-porpoise only (NP) for the inshore areas (A1, A3, A4 and A5) in 1972, 1973 and 1974. Table 4 gives a breakdown of the non-regulated logged catches for those years. 1972 was a predominant porpoise-fish year both inshore and offshore; the rough estimates of inshore fishing power reflect this, with the estimates for both the two modes combined and the porpoise only being relatively high and roughly equivalent. The relatively high index of non-porpoise fishing power was due to the fact that there was no real inshore "run" (high concentration in a time-area stratum) of non-porpoise fish in 1972, and thus larger boats maintained an advantage over small boats similar to that observed in the offshore porpoise fishery (due mainly to greater speed, searching capabilities and holding capacities, and more efficient crews). 1973 was about equally balanced between porpoise and non-porpoise fishing. In the second quarter of the year a high concentration of small (50-70cm) non-porpoise fish appeared off the coast of southern Central America, and a great deal of effort was concentrated on them. However, there was very little porpoise fishing in this time-area stratum. Thus Table 3 shows a relatively high index of porpoise fishing power and a much lower index of non-porpoise fishing power for the inshore areas in 1973. Again, when the two modes are combined the index of relative fishing power lies between the two extremes. 1974 was predominantly a non-porpoise fish year, as can be seen in Table 4. The interesting thing to note is that the index of inshore porpoise fishing power is very low in this year. This appears to be due to the fact that a major portion of the fleet operated in a relatively small area off the coast of Costa

Rica for most of the open season, fishing a high concentration of mixed schools of small yellowfin and skipjack in the non-porpoise mode. A great deal of the inshore porpoise fishing was opportunistic in that porpoise schools were not actively pursued but were only set upon when they entered the area of the of non-porpoise fishery. Thus the pursuit advantages of the large boats over the small boats were essentially negated in both modes of fishing in 1974. This is reflected in the indices of fishing power in Table 3.

Thus, as far as using estimates of CPUE for standardizing fishing effort and subsequently estimating relative stock abundances, one concludes that:

1) Careful consideration of modes of fishing should be taken into account before standardization is undertaken.

2) There are substantial differences in the relative effectiveness of purse seiners, depending on their modes of operation. In the eastern Pacific there appear to be several fishing modes which require consideration in subsequent analyses.

3) Relative efficiency is not independent of the species of tuna being caught (Table 2).

Secondly, the Robson model (6) was used to estimate relative annual yellowfin abundance for 1970-1974. Estimates were only made for the categories which demonstrate no time-area x vessel size-class interaction in Table 1. The results are presented in Table 5. For each category, normalized ratios (ratio of an annual estimate to the mean estimate over the 5-year period) of relative abundance are presented. Thus within a given year direct comparisons between estimates of a relative abundance cannot be made. The estimates for the total (P + NP) inshore catch and effort, and for the porpoise offshore catch and effort are probably fairly accurate reflections of relative stock biomass, since in order to index stock biomass the base data must reflect an unbiased sampling of the time-area strata involved. Thus both the porpoise and non-porpoise effort must be taken into account in order to sample the inshore areas in as unbiased a manner as possible. On the other hand, an overwhelming majority of the offshore catch is made in the porpoise mode of fishing, and to sample this area in as unbiased a manner as possible only the porpoise fishing need be considered. It appears that in both the inshore and offshore areas the relative abundance was high in 1970 and has declined since then. The increase in inshore total abundance in 1973 and 1974 can be attributed to the influx of available non-porpoise fish in those years. The estimates in Table 5 for the inshore porpoise and non-porpoise fisheries are certainly not indices of relative stock biomass. They are more likely estimates of relative conditional catchability in the two modes of fishing from year to year, conditional catchability referring to the probability of encountering and capturing yellowfin given that the effort is in a particular mode of operation. What these indices reflect is that in years where fishing occurs in predominantly one mode, (1972 for porpoise, 1973 and 1974 for non-porpoise) vessels are reluctant to transfer into the other mode of fishing unless the short-term prospects in the other mode are quite good.

POPULATION PRODUCTION

The objective of this section is to investigate the effects of modal fishing and areal expansion on estimates of population production. This objective was pursued with the aid of TUNPOP, an age-structured computer simulation model of the interaction of the yellowfin tuna population and the surface tuna fishery of the eastern Pacific Ocean. The model is described by Francis (1974) The effects of three phenomena were studied in detail in simulating abstractions of conditions that may have prevailed in the evolution and development of the eastern Pacific purse-seine fishery for yellowfin tuna.

First, the simulated population was divided into two exploitable segments by age-specific modes of fishing. Fish less than or equal to 85 cm in fork length (first 6 quarters in the fishery) were exploited in the non-porpoise fishery, and fish greater than 85 cm in fork length (last 12 quarters in the fishery) were exploited in the porpoise fishery. Simulated effort was generated separately in these two segments of the fishery. Letting

f_p = porpoise effort per unit of time and

f_{np} = non-porpoise effort per unit of time,

surplus production (equilibrium yield) was studied as functions of both total effort ($f_p + f_{np}$) and the relative distribution of effort between the two modes of fishing ($r_p = f_p/f_{np}$).

Second, availability (Francis 1974: page 7) of both segments of the population to the fishery was systematically varied. Recruitment to the underlying population was assumed to be constant (41.8 million fish per year recruited at 40 cm). However, fishing years were categorized as to the mode of fishing (porpoise or non-porpoise) that predominated. In a non-porpoise year, fish became fully available to the fishery at 40 cm. This was meant to represent years when large concentrations of small fish are available to the fishery along the coastline of Central and South America (1973 and 1974 for example). In a porpoise year, fish were not fully available to the fishery until they surpassed 85 cm and were recruited into the porpoise fishery. Thus the predominant mode of fishing employed by the fleet in a given year was dictated by the availability of small fish. (There are indications in the eastern Pacific yellowfin fishery that small-fish availability is closely tied to the temperature distribution in the water column.) The availability of non-porpoise fish was estimated to be 0.66 during porpoise years due to the fact that Murphy (1965) estimates of annual recruitment of 40 cm fish prior to offshore expansion (early 1960's) averaged approximately 0.66 times the estimated values after offshore expansion (late 1960's). Thus one might hypothesize that, on the average, approximately two thirds of the small fish in the population are available to the inshore non-porpoise fishery. The availability of non-porpoise fish was estimated to be 1.00 during non-porpoise years, following the hypothesis that at certain favorable times a great majority of the small fish in the population are available to the inshore non-porpoise fishery.

Finally, the effects of offshore expansion of the porpoise fishery were examined by systematically varying the availability of large porpoise fish (>85 cm). Since the offshore expansions of the 1960's approximately doubled the area being exploited. availability of the age classes which make up the porpoise fishery were varied between 0.50 and 1.00.

The basic population simulator can thus be summarized as follows:

1) The population was divided into two age-specific segments, non-porpoise and porpoise, each of which was subjected to a separate mode of fishing.

2) The availability of non-porpoise fish (≤ 85 cm) varied from 0.66 (low availability) to 1.00 (high availability) and affected the relative distribution of effort between the two modes of fishing.

3) The availability of porpoise fish (>85 cm) varied from 0.50 to 1.00 in order to represent the areal expansion of the porpoise fishery in the eastern Pacific.

4) Instantaneous mixing within all age-classes occurred at the end of each simulated quarter, thus prohibiting full areal stratifications of the simulated population.

Estimates of age-specific catchability (vulnerability) employed in the simulations were obtain from Murphy (1965) estimates of age-specific fishing mortality ($F/f = q$). Estimates for the non-porpoise fishery (fish ≤ 85 cm) were computed as averages of the age-specific instantanous fishing mortality rates for 1963-1965, years when the non-porpoise fishery operated year around. Estimates for the porpoise fishery (>85 cm) were computed as averages of the Murphy method age-specific instantaneous fishing mortality rates for 1969 and 1970, years when the porpoise fishery had expanded offshore and was operating at full capacity. Direct estimates could be made only for age classes available to the porpoise fishery during the first two quarters of the year, due to the fact that the fishery was regulated during the last two quarters of those years. Estimates of age-specific fishing mortality on those age-classes available to the porpoise fishery during the last two quarters were made by multiplying the ratio of average age-specific fishing mortality during the last two quarters of 1963-1965 to average age-specific fishing mortality during the first two quarters of 1963-1965 (years when non-regulated fishing occurred throughout the year) by the average age-specific fishing mortality during the first two quarters of 1969 and 1970.

Thus

$$F_{69-70}(3,4) = \frac{F_{63-65}(3,4)}{F_{63-65}(1,2)} \; F_{69-70}(1,2)$$

where

$F_i\,(j,k)$ = estimate of average age-specific fishing mortality during the year interval i in quarters j and k,

The estimates are given in Table 6. Note that two cohorts are assumed to be recruited to the fishery each year. The X group is assumed to be recruited at the beginning of the first quarter of the year and the Y group at the beginning of the third quarter of the year, both at 40 cm. The remainder of the model parameters were similar to those used in the example runs in Francis (1974).

TUNPØP was first used to look at the relationships of equilibrium yield (surplus production) to population biomass and equilibrium effort. Letting

ρ_{np} = availability of non-porpoise age-classes and

ρ_p = availability of porpoise age-classes,

the following five cases were simulated:

1) $r_p = 0.0$, $\rho_{np} = 0.66$ - all effort applied to the non-porpoise fishery during a porpoise year;

2) $r_p = \infty$, $\rho_p = 1.0$ - all effort applied to the porpoise fishery with both inshore and offshore fishing;

3) $r_p = 0.33$, $\rho_{np} = 1.0$, $\rho_p = 0.5$ - three times as much effort applied to the non-porpoise fishery as the porpoise fishery in a non-porpoise year with inshore fishing only;

4) $r_p = 1.0$, $\rho_{np} = \rho_p = 1.0$ - equal effort in the two modes in a non-porpoise year with both inshore and offshore fishing;

5) $r_p = 3.0$, $\rho_{np} = 0.66$, $\rho_p = 1.0$ - three times as much porpoise effort as non-porpoise effort, porpoise year with both inshore and offshore fishing.

Cases 1) and 2) are the two extremes as far as equilibrium yield is concerned, case 1) reflecting the minimum potential of the non-porpoise fishery alone and case 2) reflecting the maximum potential of the fully-expanded porpoise fishery alone. Case 3) reflects what might have occurred during the early inshore purse-seine fishery when methods of porpoise fishing were being developed. Case 4) reflects what possibly occurs during a recent non-porpoise year such as 1973, and case 5) reflects what possibly occurs during a recent porpoise year such as 1972. The results of the equilibrium yield simulations are presented in Figures 5 and 6. Several things become apparent on inspection of these figures:

1) Under a constant recruitment pattern it is advantageous from an equilibrium yield strategy to devote as much effort as possible to the porpoise fishery.

2) There is a potential difference of about 10% between the maximum sustained yield (MSY) under the hypothesized present-day predominant porpoise fishery (5) and the hypothesized present-day predominant non-porpoise fishery (4). This is probably a minimum estimate, since TUNPOP is constructed so as to produce instantaneous mixing of all fish of a given age at the end of each unit time period (quarter). Under more realistic conditions the available and unavailable portions of either the porpoise or non-porpoise populations would be stratified on an areal basis, thus increasing the equilibrium yield during porpoise years due to a reduction in the contribution of the non-porpoise segment and a subsequent increase in the contribution of the porpoise segment to the MSY.

3) The effort which produces the MSY, f_e, in a hypothesized present-day non-porpoise year (4) is virtually the same as that in a hypothesized present-day porpoise year (5). The principal difference between the two is the magnitude of the MSY.

Finally a 30-year run of TUNPOP was made to simulate the hypothetical development of the eastern Pacific yellowfin fishery. The key model parameters for the simulation are given in Table 7. The first 10 simulated years reflect a development of the inshore non-porpoise fishery. Only one fourth of the effort is devoted to the porpoise mode of fishing ($r_p = 0.33$) and only one-half of the porpoise population is available to the fishery at any time ($\rho_p = 0.50$). Fishing effort is gradually increased over time. The second 10 simulated years reflect a development of the porpoise fishery, both from the point of view of a shift of the balance of the effort to porpoise fishing (r_p increasing) and an expansion of the fishery offshore ($\rho_p \rightarrow 1.0$) The final 10 simulated years reflects the modern purse-seine fishery. Effort continues to increase and produces a mild over-exploitation of the population. Running through the entire simulation are 5-year patterns of relative porpoise and non-porpoise fishing years. In the first year of each 5-year period only first-year non-porpoise fish are fully available to the gear, in the second year all non-porpoise fish are fully available, in the third year only second year non-porpoise fish are fully available, and the fourth and fifth years no non-porpoise fish are fully available ($r_{np} = 0.66$). Correspondingly in the final 20 years of the simulation, effort shifts from predominantly non-porpoise in the first two years of each five year period to predominantly porpoise in the last three years. The results of the simulation are presented in Figure 7. It is interesting to note the hypothesized structure of the modern fishery. The largest catch always takes place in the first non-porpoise year (16,21,26) when there is still a good deal of activity and available fish left in the porpoise fishery. The lowest catch always occurs in the first porpoise year (18,23,28) after there has been several years of relatively low recruitment to the porpoise fishery coupled with a low availability in the non-porpoise fishery. The total catch increases during the two final porpoise years of each 5-year cycle.

The most commonly used vehicle for estimation of surplus production, the generalized stock production model (GENPRØD) of Pella and Tomlinson (1969), was fit to the catch and effort data from the 30-year simulation to compare its estimates of equilibrium yield parameters with similar values obtained in the equilibrium yield simulations mentioned earlier. The basic GENPRØD model is

$$\frac{dP}{dt} = HP^m - KP - \frac{dC}{dt} \tag{7}$$

where H, K and m are the three estimable parameters of the population production model.

P = population biomass,

C = catch in weight, and

$\frac{dC}{dt} = q\, fP$

where

q = catchability coefficient and

f = fishing effort

The combinations of model parameters which are of interest in terms of fishery dynamics are:

C_{max} = maximum equilibrium catch,

q = catchability coefficient,

f_{opt} = effort which produces C_{max},

$F_{opt} = qf_{opt}$ = instantaneous fishing mortality rate which produces C_{max}.

Note that this notation differs slightly from that of Pella and Tomlinson (1969). Plots of equilibrium yield against average population biomass and equilibrium effort are given in Figures 8 and 9 for the GENPRØD best fit and the two boundary conditions over which the simulation was made ($r_p = 0.33$, $\rho_{np} = 1.0$, $\rho_p = 0.5$-Case 3; $r_p = 3.0$, $\rho_{np} = 0.66$, $\rho_p = 1.0$-Case 5). The corresponding estimates of C_{max}, q, f_{opt} and F_{opt} are presented below:

Source	$C_{max} \times 10^8$	q	f_{opt}	F_{opt}
Case 3) - $r_p = 0.33$, $\rho_{np} = 1.0$, $\rho_p = 0.5$	2.30	0.24	4.0	0.98
Case 5) $r_p = 3.0$, $\rho_{np} = 0.66$, $\rho_p = 1.0$	3.05	0.35	2.0	0.69
GENPRØD best fit	2.85	0.09	3.3	0.30

Several things are of interest to note in this example:

1) The GENPRØD estimate of F_{opt} falls completely out of the range of values that one might expect from knowing the structure of the underlying population. This is most likely due to the effects of the offshore expansion of the porpoise fishery, since GENPRØD estimates of f_{opt} and F_{opt} for a similar 30-year simulation, where the entire porpoise population was always fully available to the fishery, fall well within their expected ranges given by simulations of the underlieing equilibrium yield structure.

2) The variable "P" in GENPRØD may have little relationship to the true underlying population biomass.

From the results of this analysis one might surmize that the yellowfin tuna population in the eastern Pacific is capable of producing both more than and less than our current GENPRØD estimates of MSY, dependent upon the distribution of effort in both space and mode of fishing.

Finally, in an attempt to account for the change in availability over the 30-year simulation, a modified version of GENPRØD was fit to the simulated catch and effort data. The production model itself has the same form as (7). The modification occurs in the instantaneous catch equation,

$$\frac{dC}{dt} = \frac{dC_1}{dt} + \frac{dC_2}{dt} = q_1 f_1 \rho_1 P + q_2 f_2 \rho_2 P$$

where

C_1 = catch of non-porpoise fish,

C_2 = catch of porpoise fish,

q_1 = catchability coefficient on those fish available to the non-porpoise fishery,

q_2 = catchability coefficient on those fish available to the porpoise fishery,

f_1 = non-porpoise effort,

f_2 = porpoise effort,

ρ_1 = fraction of the total population biomass available to the non-porpoise fishery, and

ρ_2 = fraction of the total population biomass available to the porpoise fishery.

The two availability variables, ρ_1 and ρ_2, were computed for each simulated year from the TUNPØP output variables. These values (Table 8) were then used as input variables to the modified GENPRØD, along with the corresponding values of catch and effort. It is interesting to note that in this simulation the fraction of the total biomass available to the porpoise fishery changes very little over the 30 simulated years. However, during the middle 10 years, when the simulated fishery was expanding, the fraction of the total biomass available to the non-porpoise fishery approximately doubled. This was due to the fact that the middle-years expansion took place in the porpoise fishery, reducing the standing stock of large porpoise fish as they became increasingly more available. On the other hand, the standing stock of non-porpoise fish remained relatively constant, as did their availability. The result was a rather significant change in the relative distribution of available non-porpoise to porpoise fish, and, obviously a much more efficient utilization of the total population biomass. Fitting the modified version of GENPRØD resulted in a 67% decrease in the sum of squared deviations of observed from expected total catch in weight. The estimate of F_{opt} = 0.72 falls within the range of the expected extremes. Plots of equilibrium yield against average population biomass and instantaneous fishing mortality ($F = q_1 f_1 \rho_1 + q_2 f_2 \rho_2$) are given in Figures 10 and 11. One can see that accounting for availability in this way brings the GENPRØD estimates back into a usable range. Of course, the real problem with this approach is that, as yet, there is no way to estimate availability from the data for the tuna fishery.

In summary I believe that two main points arise from this section:

1) The distribution of effort over both space and modes of fishing has a significant effect on yellowfin production in the eastern Pacific. One would surmise that this is also true in the eastern Atlantic, where various types of gear (baitboat, purse seine, longline) appear to exploit different age-specific segments of the yellowfin population;

2) One must be extremely careful to make sure that the assumptions of the generalized stock production model (GENPRØD) are satisfied before it is applied to fishery assessment problems. In particular one must satisfy the assumptions of a closed population and constant catchability in order for the GENPRØD estimates to be meaningful.

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FIGURE CAPTIONS

FIGURE 1. Historic and offshore areas of CYRA

FIGURE 2 Commission Yellowfin Regulatory Area (CYRA).

FIGURE 3. Areal stratification of the CYRA.

FIGURE 4. Commission length frequency (market measurement) sampling areas.

FIGURE 5. Equilibrium catch against average population biomass.

FIGURE 6. Equilibrium catch against equilibrium effort.

FIGURE 7. Catch against total effort for 30 year simulation.

FIGURE 8. Estimates of equilibrium catch against population biomass for 30 year simulation.

FIGURE 9. Estimates of equilibrium catch against equilibrium effort for GENPRØD fit to 30 year simulation.

FIGURE 10. Estimates of equilibrium catch against population biomass for modified GENPRØD fit to 30 year simulation.

FIGURE 11. Estimates equilibrium catch against fishing mortality for 30 year simulation.

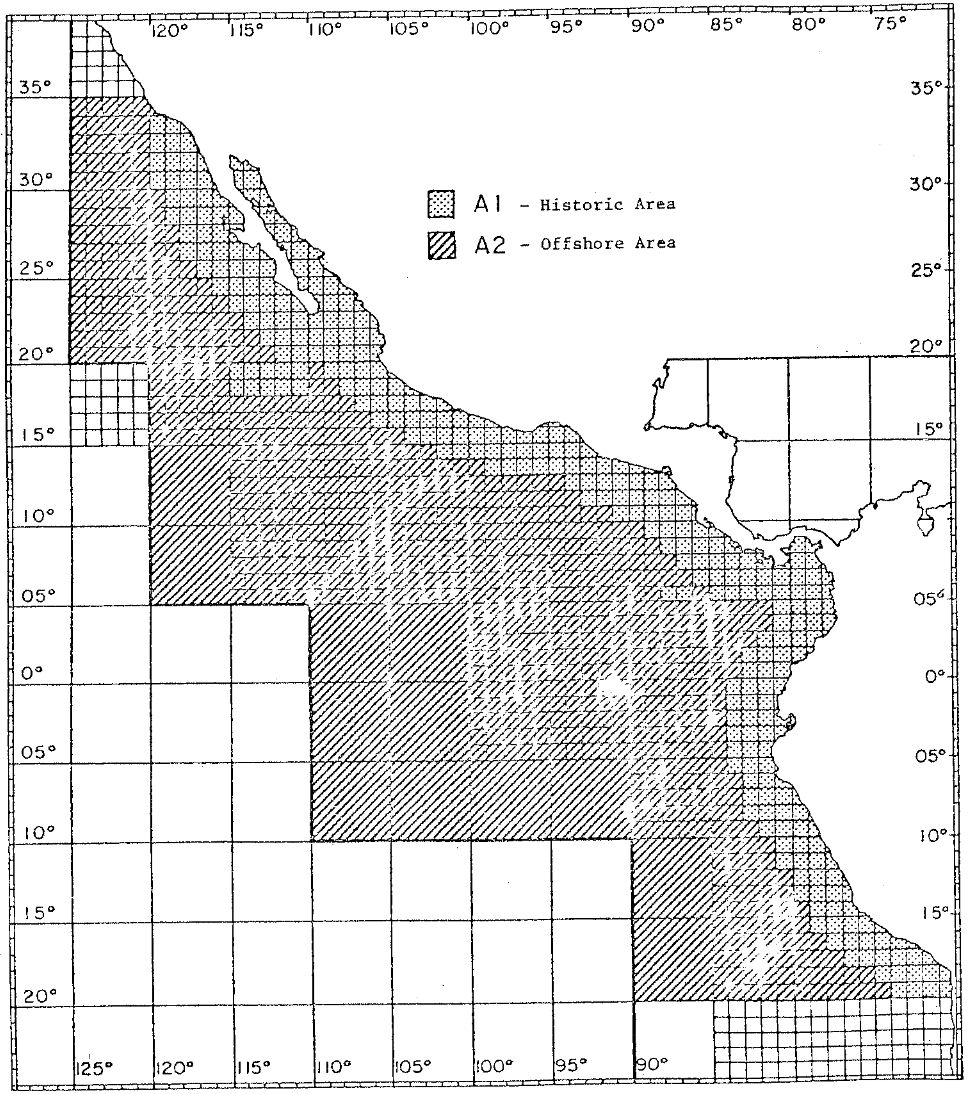


Figure 1. Historic and offshore areas of CYRA.

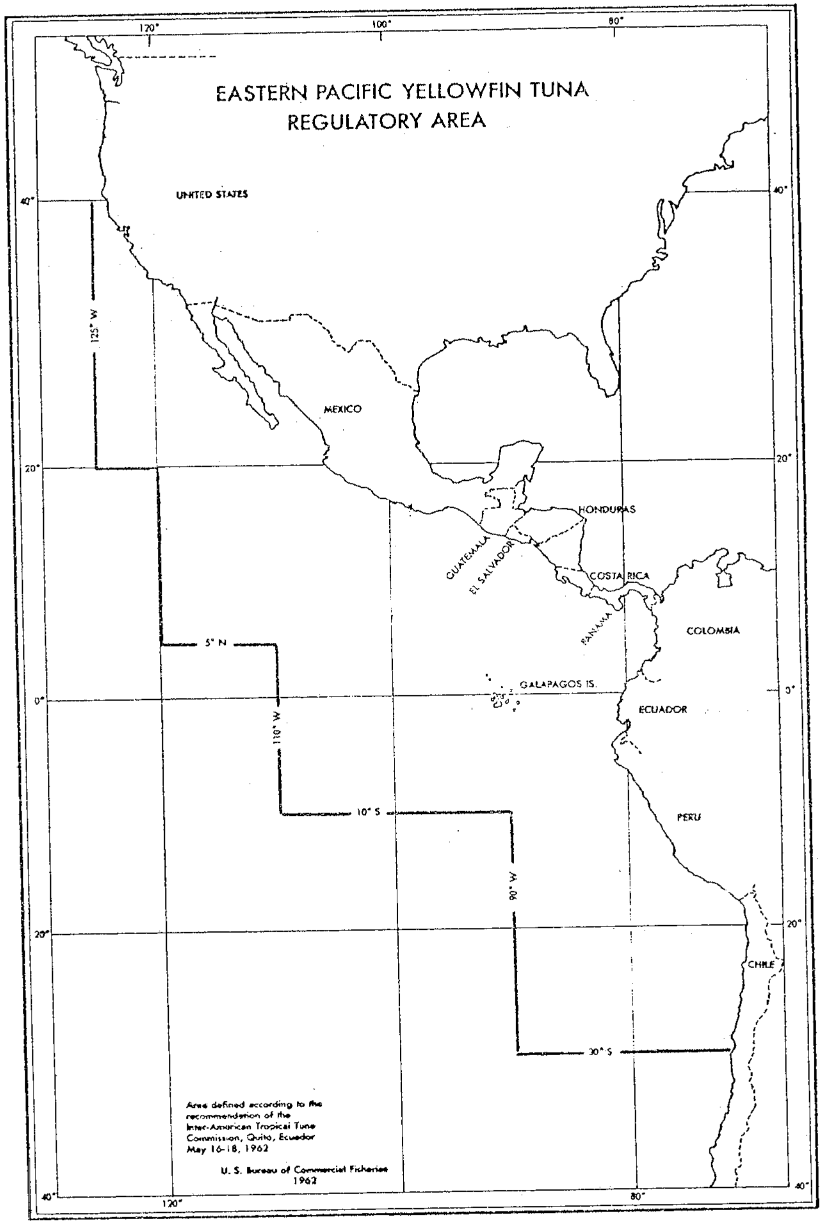


Figure 2. Commission Yellowfin Regulatory Area (CYRA)

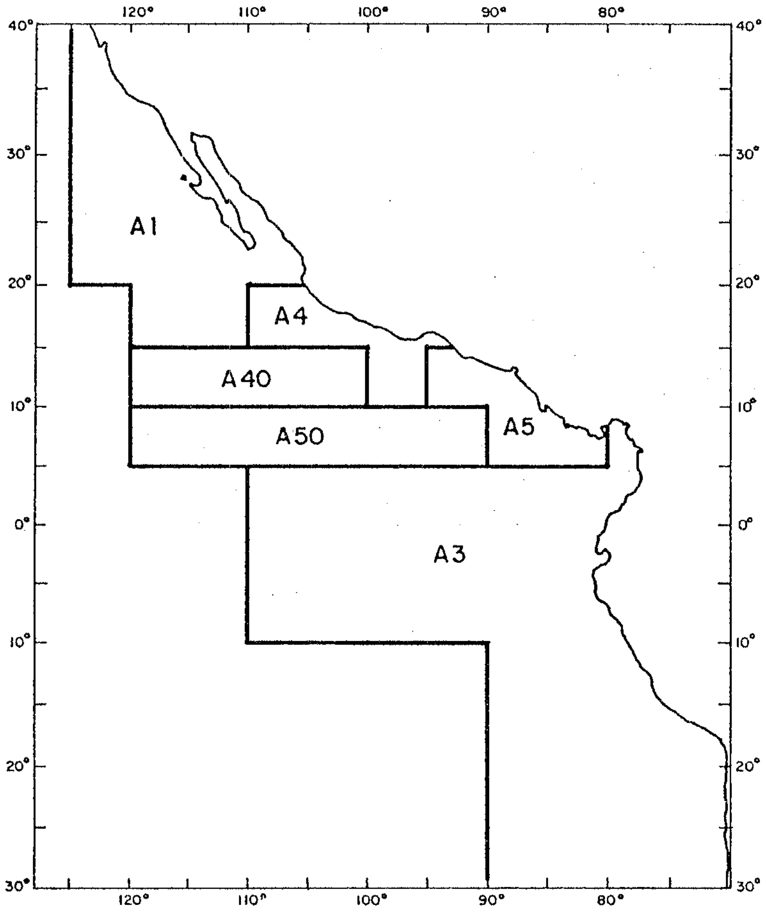


Figure 3. Areal stratification of the CYRA.

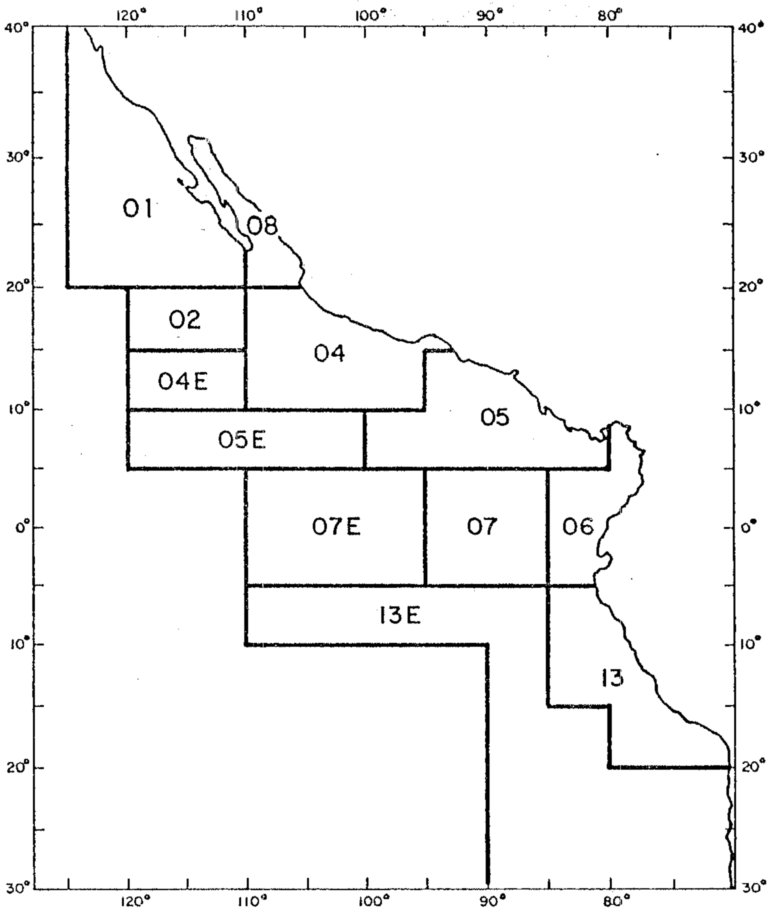


Figure 4. Commission length frequency (market measurement) sampling areas.

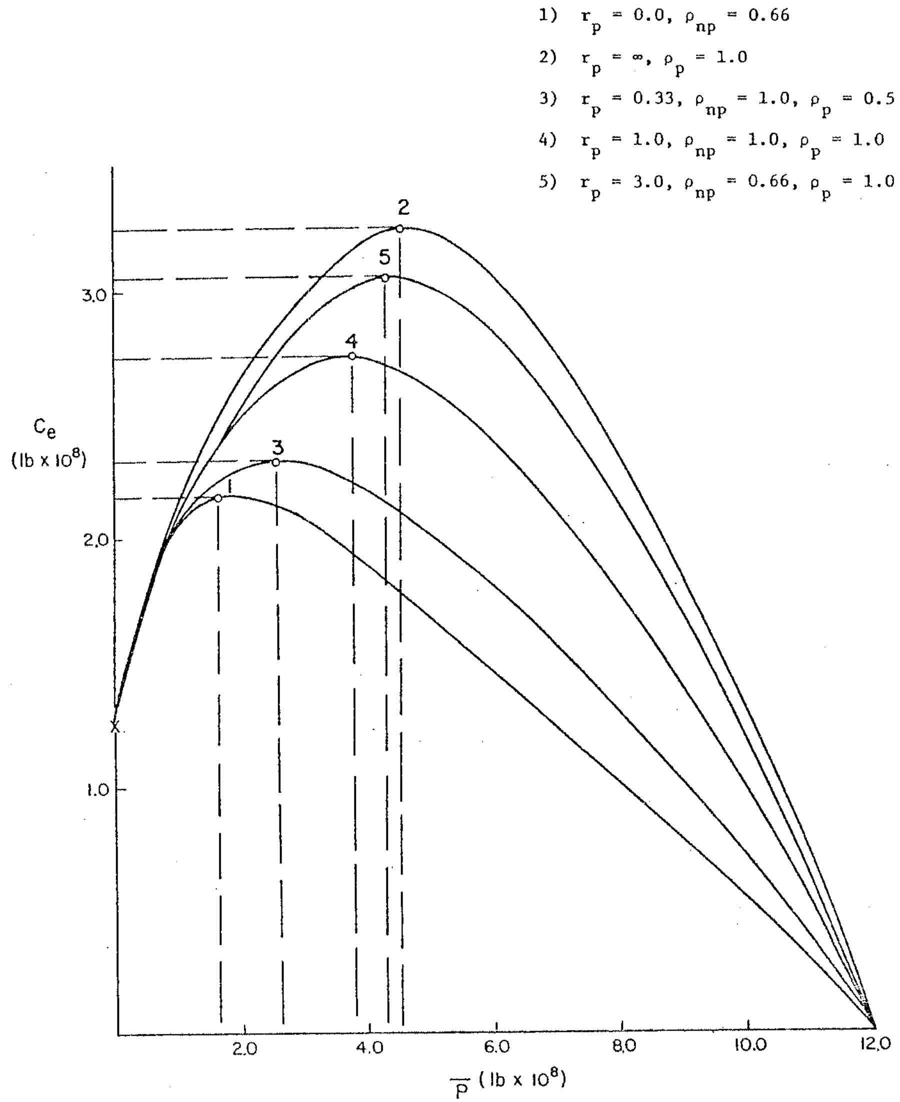


Figure 5. Equilibrium catch against average population biomass.

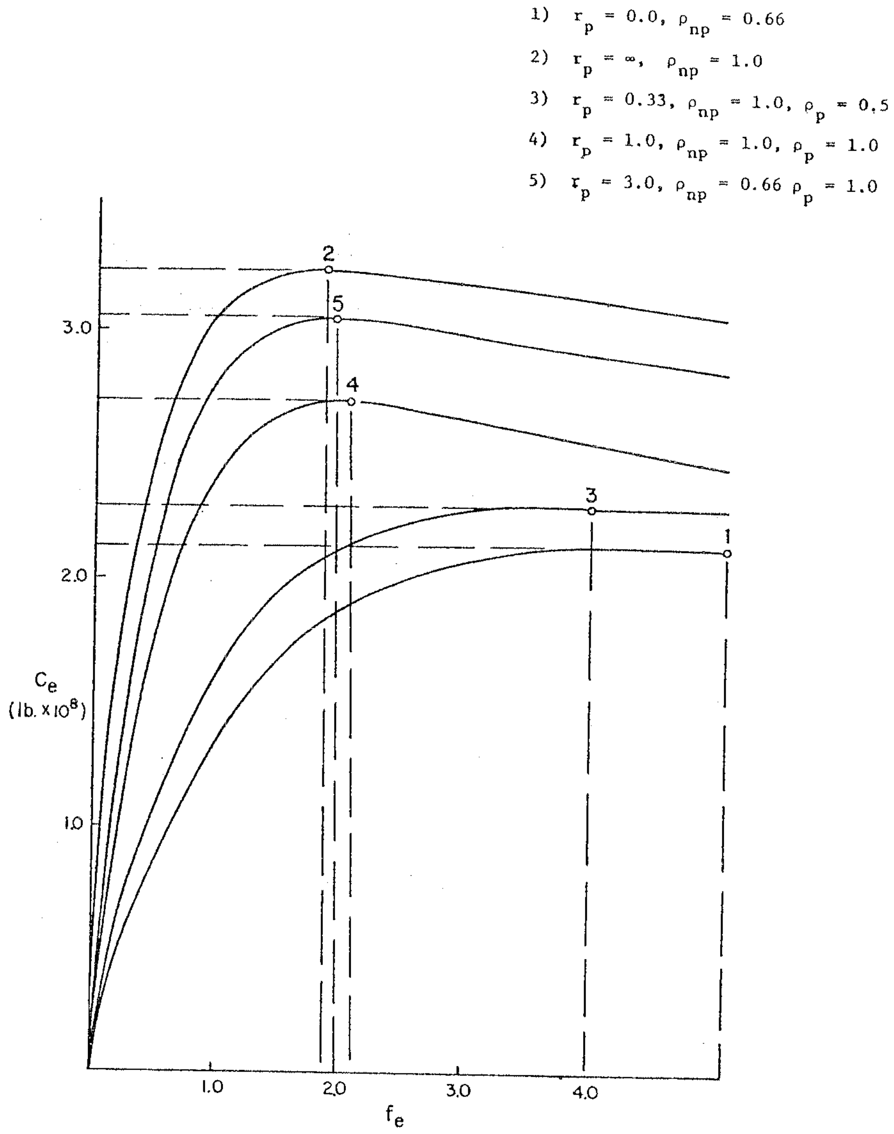


Figure 6. Equilibrium catch against equilibrium effort.

Figure 7. Catch against total effort for 30 year simulation.

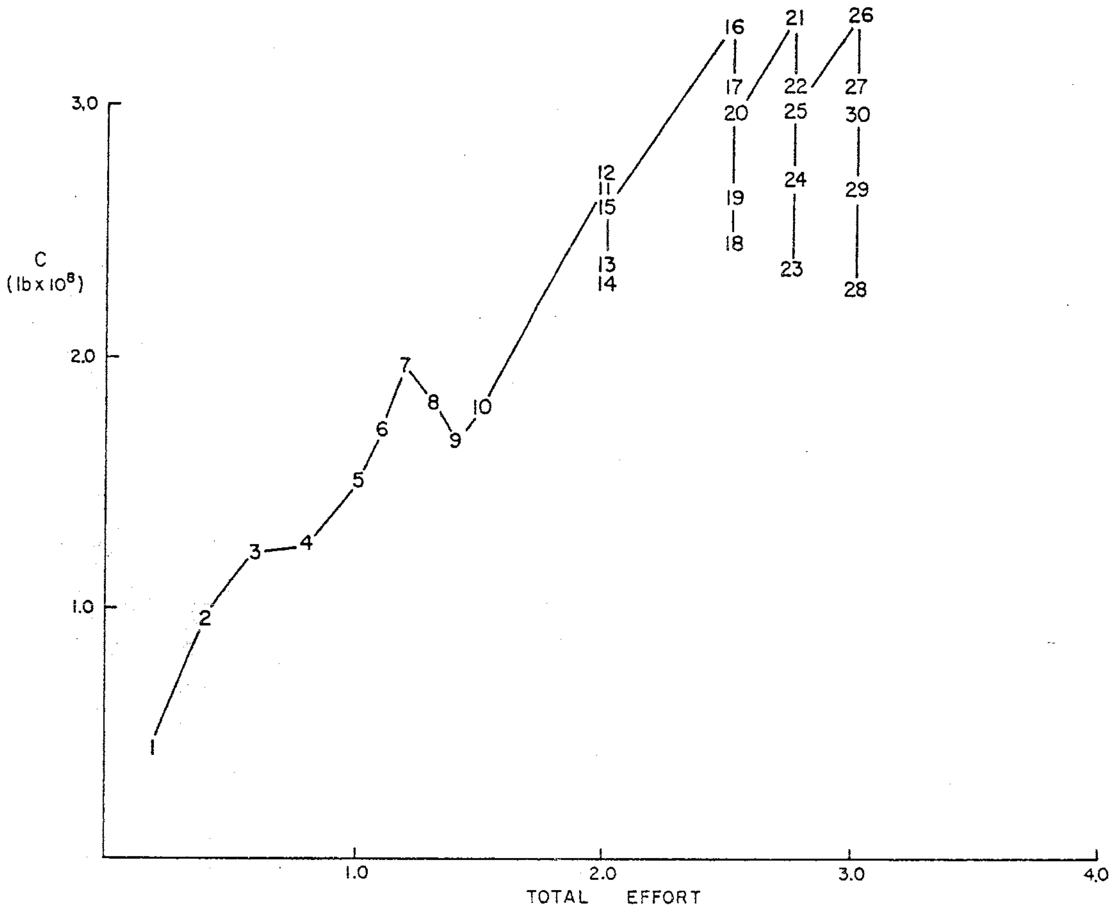
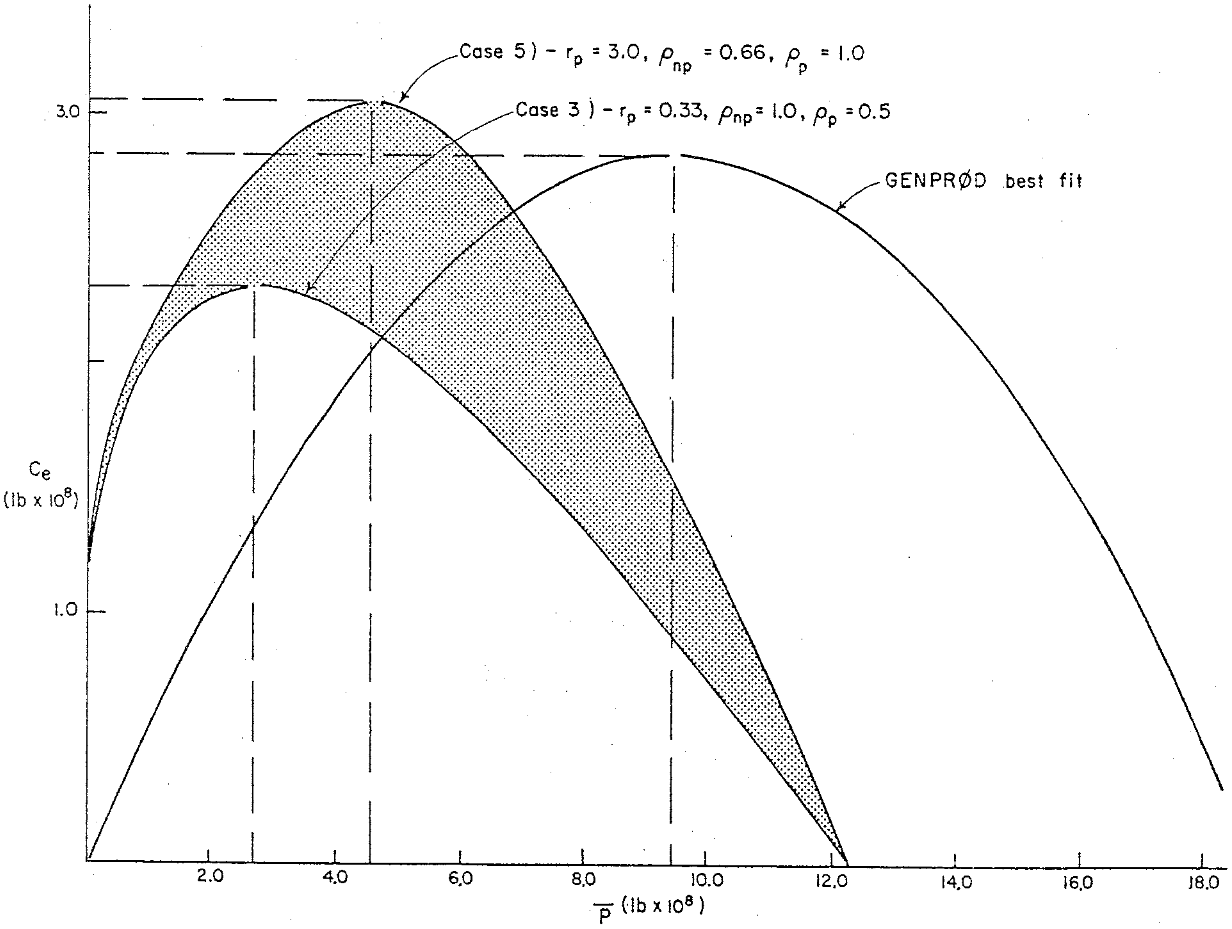


Figure 8. Estimate of equilibrium catch against population biomass for 30 year simulation.



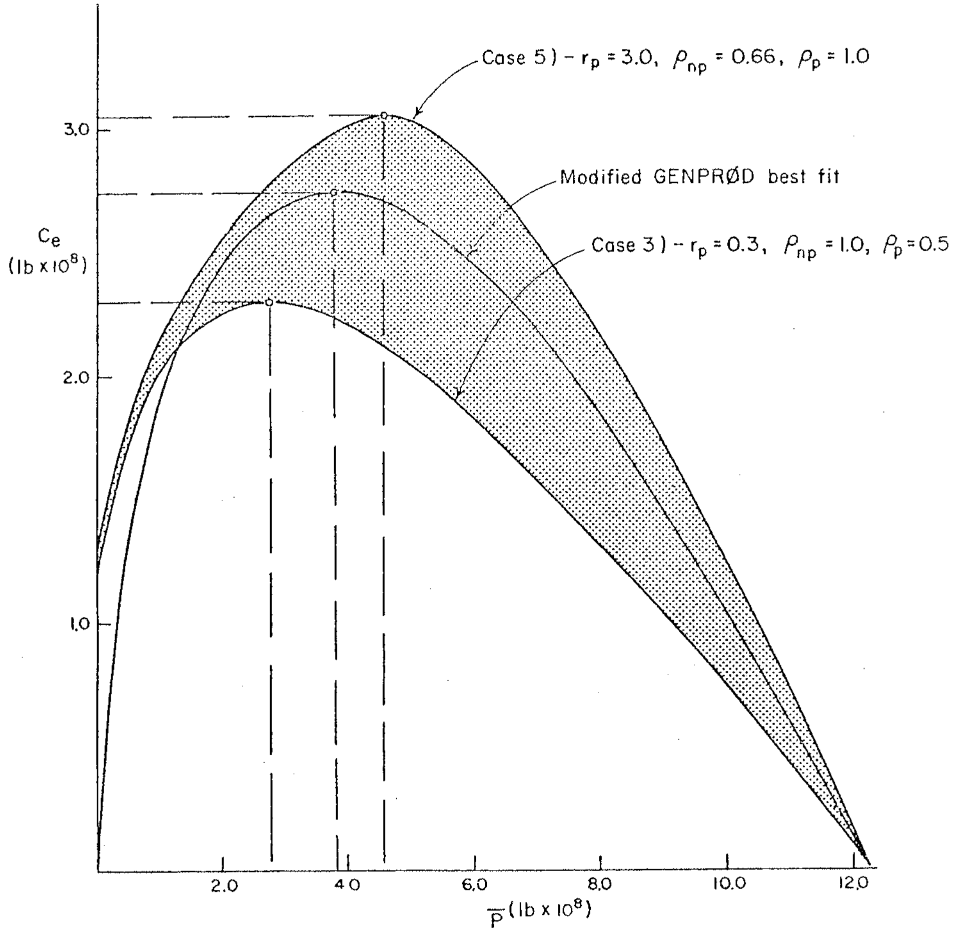


Figure 10. Estimates of equilibrium catch against population biomass for modified GENPRØD fit to 30 year simulation.

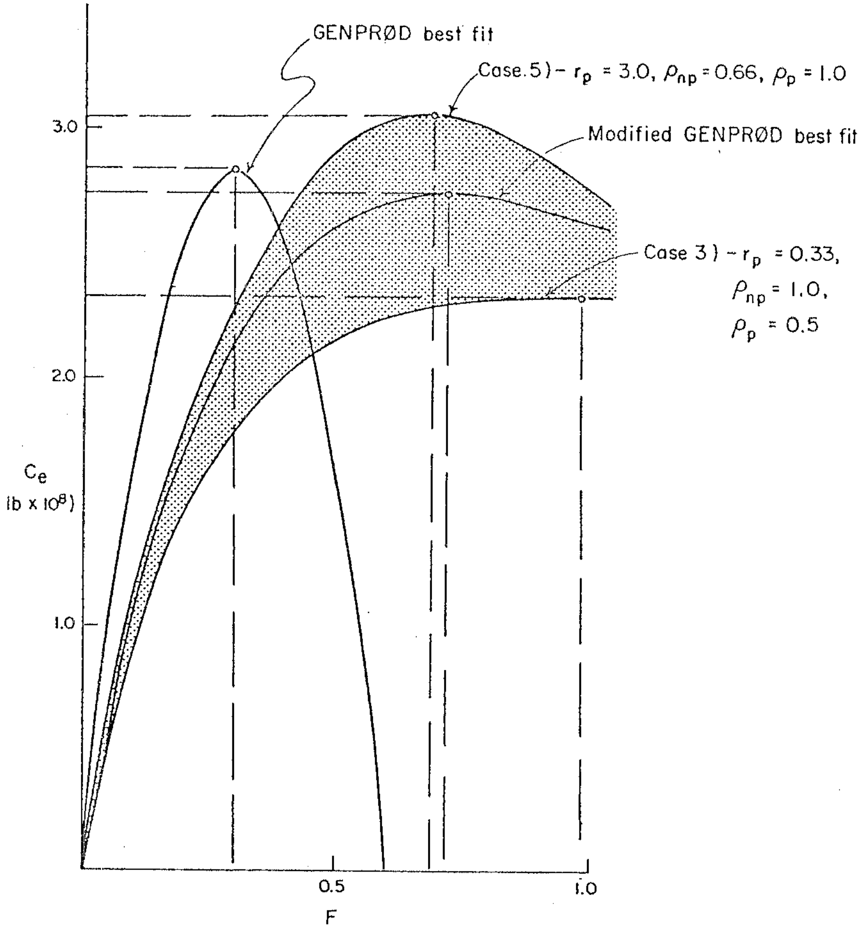


Figure 11. Estimates of equilibrium catch against fishing mortality for 30 year simulation.

Figure 9. Estimates of equilibrium catch against equilibrium effort for GENPRØD fit to 30 year simulation.

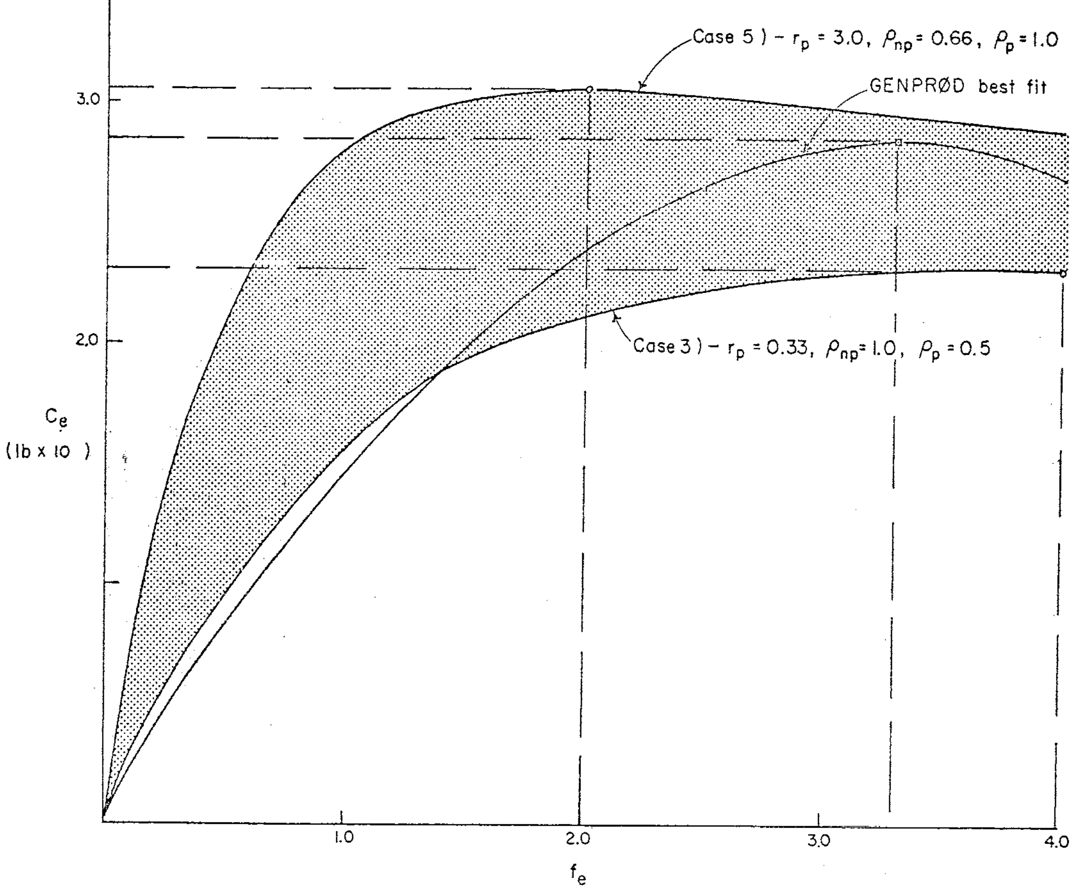


Table 1. Levels of significance for analysis of variance tests.

	Total (P+NP)			P			NP
Source	Inshore	Offshore	Inshore + Offshore	Inshore	Offshore	Inshore + Offshore	Inshore
Year (Y)	.01	.01	.01	.10	.05	.05	.01
Area (A)	.01	.25	.01	ns.	.25	.10	.01
Quarter (Q)	.01	.05	.01	.25	.10	.05	.05
Vessel size-class (V)	.01	.01	.01	.01	.01	.01	.01
YA	.01	.10	.01	.10	.05	.01	.25
YQ	.01	ns	.01	.05	ns	.10	.01
YV	ns	.25	.10	ns	ns	.25	ns
AQ	ns	.05	.10	ns	.01	.25	.25
AV	ns	ns	ns	ns	ns	ns	
QV	ns	ns	ns	ns	ns	ns	ns

Table 2. Estimates of fishing power of size-class 2 ($\geq$ 600 tons) relative to size-class 1 (<600 ton) for 1970-1974.

	Area	Fishing Power
Total (P+NP)	Inshore	1.86
	Offshore	1.68
	Inshore and Offshore	1.80
Porpoise	Inshore	2.47
	Offshore	1.70
	Inshore and Offshore	2.18
Non-Porpoise YF	Inshore	1.43
Non-porpoise YF and SJ	Inshore*	1.56

* 1970-1973 only.

Table 3. Inshore catch rates for 1972, 1973, 1974 non-regulated logged yellowfin fishery.

	Inshore Areas								
	P+NP			P			NP		
	CPDF(SC1)	CPDF(SC2)	CPDF(SC1)/CPDF(SC2)	CPDF(SC1)	CPDF(SC2)	CPDF(SC1)/CPDF(SC2)	CPDF(SC1)	CPDF(SC2)	CPDF(SC1)/CPDF(SC2)
1972	5.54	14.67	2.65	6.05	16.27	2.69	4.90	11.73	2.39
1973	6.15	13.00	2.11	5.67	14.90	2.63	6.60	11.62	1.76
1974*	7.80	10.70	1.37	7.78	12.35	1.59	7.81	9.77	1.25

* preliminary results.

Table 4. Non-regulated logged catch in short tons.

	Inshore		Offshore		Inshore + Offshore*	
	P	NP	P	NP	P	NP
72	45655 .70	19135 .30	43174 .90	4808 .10	88829 .79	23943 .21
73	39645 .47	44210 .53	26960 .95	1279 .05	66605 .59	45489 .41
74*	32737 .39	51653 .61	15910 .95	750 .05	48647 .48	52403 .52

* preliminary

Table 5. Robson estimates of relative yellowfin abundance (normalized ratios).

	TOTAL(P+NP)	P		NP
	Inshore	Inshore	Offshore	Inshore
1970	1.47	1.32	1.23	1.41
1971	0.71	0.96	1.14	0.49
1972	0.75	0.78	1.07	1.20
1973	1.03	0.93	0.88	0.96
1974	1.01	1.01	0.68	0.94

Table 6. Age-specific catchability estimates for TUNPØP simulations.

	Quarterly Age	q_x	q_y
	1	.0012	.0009
	2	.0723	.0196
	3	.5231	.1776
NP	4	.5924	.9927
	5	1.0755	.6608
	6	1.8933	.6130
	7	.8486	1.8865
	8	.8486	1.0296
	9	2.2541	.6246
	10	1.8507	.6246
	11	1.0137	1.2603
P	12	1.0137	1.1272
	13	1.6675	.5433
	14	1.2809	.5433
	15	.7083	1.2814
	16	.7083	.8837
	17	.0000	.0000
	18	.0000	.0000

Table 7. TUNPØP parameters for 30 year simulation.

Year	f_{tot}	r_p	ρ_p	A_f	
1	0.20	0.33	0.50	1	
2	0.40	0.33	0.50	1,2	
3	0.60	0.33	0.50	2	
4	0.80	0.33	0.50	-	Development of
5	1.00	0.33	0.50	-	NP fishery
6	1.10	0.33	0.50	1	
7	1.20	0.33	0.50	1,2	
8	1.30	0.33	0.50	2	
9	1.40	0.33	0.50	-	
10	1.50	0.33	0.50	-	
11	2.00	0.50	0.55	1	
12	2.00	0.50	0.60	1,2	
13	2.00	1.00	0.65	2	Development of
14	2.00	1.00	0.70	-	P fishery
15	2.00	1.00	0.75	-	
16	2.50	0.75	0.80	1	
17	2.50	0.75	0.85	1,2	
18	2.50	2.00	0.90	2	
19	2.50	2.00	0.95	-	
20	2.50	2.00	1.00	-	
21	2.75	1.00	1.00	1	
22	2.75	1.00	1.00	1,2	
23	2.75	3.00	1.00	2	Modern P, NP
24	2.75	3.00	1.00	-	fishery
25	2.75	3.00	1.00	-	
26	3.00	1.00	1.00	1	
27	3.00	1.00	1.00	1,2	
28	3.00	3.00	1.00	2	
29	3.00	3.00	1.00	-	
30	3.00	3.00	1.00	-	

$f_{tot} = f_{p} + f_{np}$

$r_p = f_p / f_{np}$

ρ_p = availability of porpoise fish

A_f = non-porpoise year classes fully available to fishery

Table 8. TUNPØP estimates of ρ_1 ρ_2

Year	ρ_1	ρ_2
1	.26	.30
2	.34	.30
3	.31	.28
4	.25	.27
5	.26	.27
6	.31	.26
7	.39	.26
8	.37	.23
9	.31	.22
10	.30	.24
11	.35	.26
12	.47	.26
13	.51	.22
14	.43	.23
15	.42	.28
16	.47	.31
17	.61	.29
18	.67	.20
19	.55	.23
20	.54	.27
21	.58	.30
22	.72	.27
23	.75	.18
24	.59	.21
25	.58	.24
26	.60	.29
27	.73	.25
28	.76	.15
29	.60	.19
30	.59	.22