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# A THEORETICAL EXAMINATION OF SOME ASPECTS OF THE INTERACTION BETWEEN LONGLINE AND SURFACE FISHERIES FOR TUNAS

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An unsolved problem common to many of the tuna fisheries of the world is the nature of the interaction between longline and surface fisheries for the same species. Fisheries for yellowfin tuna, albacore, bluefin tuna, and southern bluefin tuna are prosecuted by both types of gear in the Pacific, Atlantic, and Indian Oceans. Although there can be considerable overlap of sizes of fish taken by the two types of gear, in general, longline gear takes larger (older) fish. Exploitation of a tuna stock by the two types of gear presents management with the problems of determining the effect of various combinations of fishing effort by the two gears on both yield per recruit to the two gears and recruitment to the stocks. In order to make these determinations it is necessary to estimate 1) the availability[1] of the stock at each age to the two gears, 2) fishing mortality of the available portion of the stock caused by each gear, 3) natural mortality, 4) growth, 5) fecundity, and 6) the relationship between egg production and recruitment.

This paper is divided into three major sections. The first section examines the relationship between availability of the stock(s) of Atlantic yellowfin tuna to surface and longline fishing and yield per recruit to the two gears. This is a very important, and to our knowledge unexamined, aspect common to all tuna fisheries exploited by both types of gear. The second section examines the effect of age specific sex ratios of Atlantic yellowfin on 1) yield per recruit to the two types of gear, and 2) egg production. The third section examines the effect of random migration or dispersal of yellowfin on estimates of mortality and yield per recruit to each gear. We have restricted our analysis to yellowfin tuna because of familiarity with the species, but believe that the concepts that we develop apply to the other species as well.

## METHODS AND MATERIALS

With a noted exception, the growth equation $[L = 194.8 \times (1 - e^{-0.42(t - 0.67)})]$ estimated by Le Guen and Sakagawa (1973) and length-weight equation $[W = 0.0000214L^{2.9736}]$ estimated by Lenarz (1974) are used for Atlantic yellowfin tuna where L is fork length in cm, t is age in years, and W is weight in kg. Unless otherwise stated, we assumed that the annual instantaneous coefficient of natural mortality (M) is 0.8 (Hennemuth, 1961). We estimated age specific fecundity from two indices used by Hayasi et al (1972)--Table 1. Their index I was obtained from longline data by Kikawa (1966) and their index II was obtained from surface data by Joseph (1963). The fecundity indices were calculated by Hayasi et al (1972) by multiplying mean ova counts by percentage of mature fish for each age and then dividing the product by the product calculated for age 3 fish. For much of our work we used estimates of the 1967-71 average size (age) composition of the Atlantic yellowfin fishery made by Lenarz et al (1974)--Table 2. Although the data is out of date it will be referred to as current throughout the paper.

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[1] The available portion of the stock is subject to both other mortality (any mortality not caused by gear of concern) and fishing mortality caused by the gear of concern. The unavailable portion of the stock is subject only to other mortality.

Table 1. Indices of fecundity of yellowfin tuna as interpolated from Hayasi et al (1972).

| Midpoint of size interval (cm) | Fecundity index I | Fecundity index II |
|---|---|---|
| 80 | 0.04 | 0.07 |
| 85 | 0.04 | 0.14 |
| 90 | 0.05 | 0.21 |
| 95 | 0.08 | 0.27 |
| 100 | 0.15 | 0.36 |
| 105 | 0.23 | 0.42 |
| 110 | 0.33 | 0.51 |
| 115 | 0.42 | 0.61 |
| 120 | 0.55 | 0.70 |
| 125 | 0.70 | 0.81 |
| 130 | 0.88 | 0.92 |
| 135 | 1.12 | 1.04 |
| 140 | 1.40 | 1.15 |
| 145 | 1.80 | 1.26 |
| 150 | 2.30 | 1.37 |
| 155 | 2.77 | 1.50 |
| 160 | 3.20 | 1.62 |
| 165 | 3.57 | 1.76 |
| 170 | 4.05 | 1.91 |
| 175 | 4.42 | 2.06 |
| 180 | 4.82 | 2.23 |
|  | 5.01 | 2.43 |

Table 2. 1967-71 Average Catch in numbers of yellowfin tuna from the Atlantic Ocean by gear, sex, and Size, Lenarz et al (1974)

|  | MALE **** |  |  | FEMALE ****** |  |  |
|---|---|---|---|---|---|---|
| Midpoint of Size interval (cm.) | SURFACE | LONGLINE | TOTAL | SURFACE | LONGLINE | TOTAL |
| 35. | 1179. | 0. | 1179. | 1179. | 0. | 1179. |
| 40. | 14528. | 0. | 14528. | 14528. | 0. | 14528. |
| 45. | 61563. | 0. | 61563. | 61563. | 0. | 61563. |
| 50. | 186611. | 4. | 186615. | 186611. | 4. | 186615. |
| 55. | 237622. | 11. | 237633. | 237622. | 11. | 237633. |
| 60. | 210711. | 226. | 210937. | 210711. | 226. | 210937. |
| 65. | 121824. | 324. | 122148. | 121824. | 324. | 122148. |
| 70. | 137389. | 1076. | 138465. | 137389. | 1076. | 138465. |
| 75. | 102046. | 2718. | 104764. | 102046. | 2718. | 104764. |
| 80. | 90710. | 2847. | 93557. | 90710. | 2847. | 93557. |
| 85. | 67060. | 6013. | 73073. | 67060. | 6013. | 73073. |
| 90. | 52541. | 6525. | 59066. | 52541. | 6525. | 59066. |
| 95. | 51366. | 5833. | 57199. | 51366. | 5833. | 57199. |
| 100. | 56714. | 7537. | 64251. | 56714. | 7537. | 64251. |
| 105. | 52752. | 17036. | 69788. | 52752. | 17036. | 69788. |
| 110. | 51497. | 20105. | 71602. | 51497. | 20105. | 71602. |
| 115. | 35981. | 22017. | 57998. | 35981. | 22017. | 57998. |
| 120. | 26167. | 21430. | 47597. | 26167. | 21430. | 47597. |
| 125. | 30779. | 28679. | 59458. | 30779. | 28679. | 59458. |
| 130. | 26001. | 29272. | 55273. | 26001. | 29272. | 55273. |
| 135. | 21975. | 22345. | 44320. | 21975. | 22345. | 44320. |
| 140. | 16749. | 26035. | 42764. | 16749. | 26035. | 42764. |
| 145. | 26919. | 38782. | 65701. | 11661. | 16800. | 28461. |
| 150. | 31942. | 36099. | 68041. | 8450. | 9549. | 17999. |
| 155. | 24727. | 33938. | 58665. | 3767. | 5170. | 8937. |
| 160. | 18701. | 22644. | 41345. | 1524. | 1845. | 3369. |
| 165. | 14497. | 13140. | 27637. | 573. | 519. | 1092. |
| 170. | 5621. | 6162. | 11783. | 94. | 103. | 197. |
| 175. | 3703. | 240. | 3943. | 21. | 1. | 22. |
| 180. | 1836. | 55. | 1891. | 3. | 0. | 3. |
| TOTAL | 1781711. | 371093. | 2152804. | 1679456. | 254020. | 1933878. |

Estimates of size (age) specific fishing mortality ($F_t$) on an annual basis were made using the Gulland (1965) and Murphy (1965) method. The computer program COHORT, written by W. W. Fox, Jr., was used to obtain estimates for each 5 cm size interval beginning at 32.5 cm.

The computer program MGEAR, written by W. H. Lenarz, was used to obtain estimates of yield per recruit using the Ricker (1958) yield equation. The program was slightly modified to also calculate indices of egg production using the following equation

$$E_{t_1, t_2} = 0.5\,(t_2 - t_1)\,N_{t_1}\,(FI_{t_1} + FI_{t_2}\,e^{-(F_{t_1} + M_{t_1})(t_2 - t_1)})$$

where

$E_{t_1, t_2}$ = index of egg production between age $t_1$ and age $t_2$

$FI_{t_1}$ = index of fecundity for age $t_1$

$N_{t_1}$ = number of females in population of age $t_1$

$F_{t_1}$ = coefficient of instantaneous fishing mortality between age $t_1$ and age $t_2$

$M_{t_1}$ = coefficient of instantaneous natural mortality between age $t_1$ and age $t_2$.

This equation assumes that the estimates of FI are proportional to egg production which is assumed to be continuous.

We note here that Fonteneau and Lenarz (1973) unfortunately made an error in their estimates of stock fecundity by multiplying the index of fecundity by the biomass of the stock instead of the size of the stock in numbers as should have been done. A computer program MIGR was written by J. R. Zweifel to perform the calculations used for the third section of the paper. A description of the calculations will be given in the third section.

## AVAILABILITY OF THE STOCK(S) OF ATLANTIC YELLOWFIN TUNA TO SURFACE AND LONGLINE GEARS

Previous work on yield per recruit of the Atlantic yellowfin fishery has assumed that fish of all ages in the entire Atlantic are equally available to both longline and surface gears (e.g. Wise, 1972; Hayasi et al, 1972; Lenarz et al, 1974), or that yellowfin in the eastern Atlantic are equally available to both types of gear (e.g. Fonteneau and Lenarz, 1974). These are simply speculations, since in actuality, nothing is known on this subject for the Atlantic yellowfin and very little for any other tuna fishery. Serious tagging efforts have begun only recently in the Atlantic and the results of these studies have not been published. Since the surface fishery for yellowfin occurs very close to the west African coast (Fox and Lenarz, 1973) and the longline fishery for yellowfin is distributed throughout the tropical Atlantic, it seems possible that the longline fishery is exploiting some fish that are not available to the surface fishery. It is also possible that some stock(s) are available to surface fishing, but because of genetically controlled behavior or other reasons, are never available to longline fishing.

With the kind permission of W. H. Bayliff of the Inter-American Tropical Tuna Commission (IATTC) we examined yellowfin tag return data from the eastern Pacific during 1963-1966 in an attempt to evaluate the availability of fish to both gears. We tabulated the number of tag returns for fish larger than 100 cm at return by 10 cm size intervals (Table 3). All of the fish had been at liberty for at least 10 months. Although all of the tagged fish were measured when released, not all were measured when recovered. At the suggestion of Bayliff, we used the growth equation

$$L = 167 (1 - e^{-0.6(t - 0.833)})$$

estimated by Davidoff (1963) for growth of yellowfin in the eastern Pacific to estimate the size of the unmeasured returns. All of the returns were surface caught fish even though longliners captured a considerable number of yellowfin in the eastern Pacific (east of 130° W) (Kume and Joseph, 1969). In fact, for many of the 10 cm size intervals, the longliners caught more yellowfin than the surface gear (Table 4).

Again at the suggestion of Bayliff, we next estimated the expected return of tags from longline caught fish. If tag recoveries were independent of each other, recovered tags were reported at the same rate by both components of the fishery, and tagged fish were equally available to both gears; then the expected returns of tagged fish of size i by gear j in year k is given by

Table 3. Number of returns of tagged yellowfin tuna from the eastern Pacific Ocean by size interval and gear (W. H. Bayliff, personal communication).

| Size interval (cm) | 1963 | 1964 | 1965 | 1966 |
|---|---|---|---|---|
| 101-110 | 2 | 16 | 3 | 3 |
| 111-120 | 1 | 7 | 1 | 1 |
| 121-130 | 2 | 0 | 2 | 0 |
| 131-140 | 0 | 0 | 0 | 1 |
| 141-150 | 0 | 0 | 0 | 0 |
| 151-160 | 0 | 0 | 1 | 0 |

Table 4. Catch of yellowfin tuna from the eastern Pacific Ocean (east of 130° W) in hundreds of fish by size and gear (Kume and Joseph, 1969).

| Size interval (cm) | 1963 | | 1964 | | 1965 | | 1966 | |
|---|---|---|---|---|---|---|---|---|
| | Surface gear | Longline gear | Surface gear | Longline gear | Surface gear | Longline gear | Surface gear | Longline gear |
| 101-110 | 653 | 336 | 4,082 | 173 | 3,386 | 30 | 2,926 | 54 |
| 111-120 | 473 | 455 | 2,245 | 465 | 2,211 | 93 | 2,044 | 116 |
| 121-130 | 508 | 390 | 720 | 1,078 | 1,895 | 444 | 1,312 | 304 |
| 131-140 | 237 | 751 | 448 | 804 | 905 | 758 | 718 | 515 |
| 141-150 | 240 | 541 | 320 | 469 | 498 | 466 | 536 | 575 |
| 151-160 | 212 | 144 | 102 | 104 | 194 | 205 | 204 | 200 |

$$E(R_{ijk}) = R_{i\cdot k}N_{ijk}/N_{i\cdot k} \qquad (1)$$

$$i = \begin{cases} 1, \text{ when size is between 101 and 110 cm} \\ \cdot \\ \cdot \\ 6, \text{ when size is between 151 and 160 cm} \end{cases}$$

$$j = \begin{cases} 1, \text{ when fish are caught by surface gear} \\ 2, \text{ when fish are caught by longline gear} \end{cases}$$

$$k = \begin{cases} 1, \text{ when fish are caught in 1963} \\ \cdot \\ \cdot \\ 4, \text{ when fish are caught in 1966} \end{cases}$$

where

$R_{ijk}$ = number of returns

$N_{ijk}$ = number of fish caught.

A dot in the position of a subscript signifies summation of the variable over the subscript; e.g. $X_{i\cdot k} = \sum_{j=1}^{2} X_{ijk}$.

Forty fish were returned by the surface gears during 1963-1966 (Table 3). Using the statistics of Tables 3 and 4 and assuming that (1) is true, 5.4 of these tags should have been returned by the longline fishery and 34.6 by the surface fishery. The chi-square value, corrected for discontinuity, for the observed and expected returns is 5.13, with probability slightly less than 0.025. Although the chi-square is significant, the significance of the deviation from the hypothesis of independence, equal reporting rate, and equal availability is underestimated because of the necessity to combine the year and size strata. The probability under (1) of a returned tag being from a surface-caught fish ($P_{i1k}$) is

$$P_{i1k} = N_{i1k}/N_{i\cdot k} \qquad (2)$$

The exact probability of all returns being from surface-caught fish during the 1963-1966 period is

$$P_{\cdots} = \prod_{i=1}^{6} \prod_{k=1}^{4} (P_{i1k})^{R_{i1k}} \qquad (3)$$

Using the data in Tables 3 and 4, our estimate of $P_{\cdots}$ is 0.00152, which is very low and indicates that (1) does not hold. Thus we may conclude that 1) tag returns are not independent, and/or 2) longline recoveries are reported at lower rates than surface recoveries, and/or 3) the fish were not equally available to both gears. Since all fish were at liberty for more than 10 months before being recovered, the assumption of tag returns being independent seems likely to be valid. A considerable number of southern bluefin tuna have been recovered and returned by longliners (Shingu, 1970), indicating longline fishermen do cooperate in tagging programs. During the period of the study the surface fishery was only beginning to move offshore (Calkins and Chatwin, 1971), while the longline fishery was distributed throughout the area (Kume and Joseph, 1969). Also, the fish that were released were caught by surface gear, tagged and released in near-shore areas. Thus, tagged fish were probably more representative of fish exploited by the surface fishery than those that were exploited by the longline fishery, if two groups of fish existed. Thus it seems plausible that the tagged fish were not equally available to longline and surface gears. This would suggest that longliners were capturing fish that were not available to surface gears and/or that the surface fishery was exploiting fish not available to longline fishing.

It is interesting to note a paper by Hisada (1973) that showed that yellowfin tuna caught by surface gear (handlines) were of the same size as those caught by longliners in the same area and time. However, the surface-caught fish tended to be more sexually mature except in areas in which the 26° C isotherm occurred at depths fished by longliners. He attributed this phenomenon to a perference for warmer waters by sexually mature fish and noted that larvae of yellowfin tend to be found at water temperatures exceeding 26° C. Thus, there is evidence that some yellowfin behave in a fashion that makes them available to surface fishing but not longline fishing.

With the above in mind we considered three hypothetical stock structures for the Atlantic yellowfin fishery: 1) the same stock(s) are equally available to both gears; 2) half of the catch of the longline fishery comes from stock(s) not available to the surface fishery; and 3) the entire catch of the longline fishery comes from stock(s) not available to the surface fishery. The effects of the three hypotheses on estimates of fishing mortality and yield per recruit to the gears were examined.

Using the data in Table 2, we estimated size specific F under the three hypotheses (Figure 1). The final value of size-specific[1] was set at 0.2 following Lenarz et al (1974). The estimates indicate that values of F for large fish are directly related to the portion of he longline catch that comes from the stock(s) exploited by the surface fishery. The converse holds for F at small sizes. Estimates of yield per recruit were also made.

When fishing effort is at the 1967-1971 level and yield per recruit is plotted against effective size at recruitment (Figure 2), the absolute values of yield per recruit are directly related to the portion of the longline catch that comes from the stock(s) exploited by the surface fishery. The relative values of yield per recruit within a hypothesis are not significantly affected by the portion of the longline catch that comes from the stock(s) exploited by the surface fishery. Therefore, the three hypothetical stock structures do not seem to have much bearing on decisions concerning minimum size regulations.

Estimates of yield per recruit were also plotted as functions of fishing effort, size at recruitment, and portion of longline catch that comes from stock(s) exploited by the surface fishery. Again the relative values of the

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[1] Estimation of a vector of size-specific F requires an estimate of natural mortality and size-specific F for one size category. We chose to use reasonable guesses of size-specific F for the fish greater than 177.5 cm. This guess will be referred to as input F. The vector of size-specific F will be referred to as F.

results are not significantly influenced by the stock structure (Figures 3a and b). We note that Figure 3 is in agreement with the conclusion of Fox and Lenarz (1974) "that the Atlantic yellowfin fishery is approaching or has obtained a plateau where substantially increased sustainable average yield of yellowfin tuna will not be obtained by increasing fishing effort without some concomitant change in the constitution of the fishery. . .". They came to this conclusion using the production model approach under the alternative assumptions that either the longline and surface gears exploit the same or separate stock(s).

The effect of the surface fishery on the longline fishery was examined by estimating yield per recruit to the longline fishery in the presence of a surface fishery and in the absence of a surface fishery (Figure 4). The results suggest that, if the two gears exploit the same stock(s) the yield per recruit to the longline fishery is greatly reduced by the surface fishery. The same procedure was used to examine the effect of the longline fishery on the surface fishery (Figure 5). The results indicate that the yield per recruit to the surface fishery would be increased by 25% if the longline fishery ceased.

Although the presence of each fishery reduces the yield per recruit of the other, the yield per recruit of the combined fisheries is higher than the yield per recruit of either fishery alone. The results suggest that if a catch quota system is imposed on the Atlantic yellowfin fishery, all components should be included unless it is shown that different stock(s) are being exploited by the gears.

The above results (Figures 4 and 5) suggest that a stock of yellowfin will produce a potentially higher yield per recruit to a longline fishery than to a surface fishery, if the fish are equally available to the two gears. However, until the question of availability is settled, it is not possible to predict the potential production to the two gears. We point out here that gear specific availability is not well known for any tuna fishery, and would be difficult to determine. Thus, we are faced with the prospect of probably being forced to empirically determine the production potential for each gear in each fishery. After a fishery is established, an analysis of the type conducted on the Atlantic yellowfin fishery could be utilized to examine the effects of availability on yield per recruit to the two gears. If the analysis indicates that management decisions should be based on the nature of availability to the two gear types, then a tagging study probably could be designed to provide the required answers.

## EFFECTS OF AGE SPECIFIC SEX RATIOS OF ATLANTIC YELLOWFIN TUNA ON YIELD PER RECRUIT TO THE TWO TYPES OF GEAR AND STOCK FECUNDITY

While a number of authors have noted that the ratio of females to males appears to be less than one to one for larger tunas, none to my knowledge have incorporated these observations into calculations of yield per recruit or stock fecundity. Beardsley (1971) reported that the ratio of females to male Atlantic longline-caught albacore was 233:365 during the December 1969-September 1970 period. Males became increasingly dominant at sizes greater than 100 cm. Females slightly outnumbered males between 92 and 100 cm, but not enough to suggest that differential growth was the primary agent responsible for the size specific change in sex ratio (Figure 6). Bard (1973) noted Beardsley's results and recommended considering the sexes separately in studying the population dynamics of albacore, if Beardsley's results are confirmed. Sakamoto (1969) noted for Atlantic bigeye, "males predominated in areas of higher water temperature. Proportion of females increase as the water temperature gets lower." His data indicated that as size increases the proportion of females decreases and there is some evidence for females growing slower than males in waters between 30° to 50° N, but not in equatorial waters. Data presented by Kikawa (1964) indicate that southern bluefin tuna above 150 cm are predominantly males, while females often outnumber males at smaller sizes. Thus, female southern bluefin may grow slower than males. F. Mather III of the Woods Hole Oceanographic Institution, in a personal communication, remarked that his limited amount of data on Atlantic bluefin indicate that the sex ratio is closer to unity for large fish than found by some other workers. He believes that the discrepancy in these studies may be due to ovaries of large female bluefin being very fatty unless the fish are approaching spawning condition and that there may be a tendency to identify some of the fatty ovaries as testes unless the entire organs are closely examined. His remarks suggest that all of the above results are open to question and we recommend that a very careful study be carried out on the subject.

Since there is evidence for age specific changes in the sex ratio of tunas, we felt that the effects of such change on estimates of yield per recruit to each gear type and fecundity should be investigated. As no extensive studies of age specific sex ratios for Atlantic yellowfin have been published, we have assumed sex ratios to be the same as Pacific yellowfin. We used results from a study by Murphy and Shomura (1972) who found that beyond 140 cm male yellowfin greatly outnumbered females (Figure 7). The data in Figure 7 does not show any evidence for sex specific growth. Using their data we estimated that beyond 140 cm

$$\ln R = 6.74 - 1.96\,t \qquad (4)$$

where

R = ratio of females to males

t = age in years.

Assuming that males have a coefficient of instantaneous natural mortality of 0.8 on an annual basis, one interpretation of the above result is that female yellowfin larger than 140 cm have a coefficient of apparent natural mortality of 2.76 on an annual basis. Assuming that the results of Murphy and Shomura apply to the Atlantic and that all yellowfin are equally available to both gears, we separated the catch of yellowfin into males and females using (4) (Table 2), and estimated size specific F for the males using final values of size specific F of 0.2 and 0.8 (input F) (Figure 8). The estimates of size specific F are similar except for very large yellowfin. Since the differences in sex ratio only occurs at large sizes, we used both sets of estimates of F. For females, three hypotheses were examined for estimating F: 1) the observed differences in sex ratios are artifacts and consequently females have the same values of F as males (denoted as 50: 50); 2) females larger than 140 cm have a higher natural mortality rate than males but are exploited at the same rate as males for all sizes (denoted as HIGH M); and 3) females have the same natural mortality rate as males but become less subject to fishing mortality beyond 140 cm (denoted as BEH for behavior changes). The alternative hypotheses considerably effected the estimates of size specific F (Figure 8).

In the following analyses we found that the BEH and HIGH M hypotheses produce similar results. To save space, we refer to only one of the two hypotheses, viz. the one that produced results that showed the greatest difference from the 50: 50 hypothesis.

Estimates of yield per recruit at the current size at recruitment as a function of fishing effort are shown in Figure 9. The choice of input F has little effect on the relative values of yield per recruit. Yield per recruit is closer to the maximum under high input F than low input F. The curves are considerably more dome-shaped when a 50: 50 sex ratio is assumed than under the other two hypothesis. Under high input F and the 50: 50 hypothesis only a 3% increase in yield per recruit could be obtained by increasing fishing effort. Under the BEH hypothesis a 20% increase in yield per recruit could be obtained by increasing effort.

Estimates of yield per recruit at the current level of fishing effort are shown as a function of size at recruitment in Figure 10. Again the choice of input F has little effect on the relative values of yield per recruit. A slightly greater dependence of yield per recruit on minimum size is obtained when the high input F is used. Under high input F and the 50: 50 hypothesis a 10% increase in yield per recruit could be achieved by increasing size at recruitment. Under the BEH hypothesis only a 5% increase would occur. Eumetric fishing occurs when size at recruitment is raised from the current 32.5 cm to 82.5 cm under the 50: 50 hypothesis and 72.5 cm under the BEH hypothesis.

Estimates of yield per recruit under the current size at recruitment as a function of fishing effort were also calculated for each gear (Figure 11). The results show that the curves are more dome-shaped for the longline fishery than for the surface fishery under all three hypotheses. Furthermore, the longline fishery is more sensitive to fishing effort under the 50: 50 hypothesis than under the other two. The curves for the surface fishery are dome-shaped under the 50: 50 hypothesis, but appear to approach an asymptote under the other two.

We also estimated yield per recruit at the current size of recruitment for each gear when the other gear is not exploiting the stock (Figure 12). A comparison of Figures 11 and 12 reveals that yield per recruit to the longline fishery would increase by about 115% if surface fishing were eliminated under high input F and the 50: 50 hypothesis and 76% under high input F and the BEH hypothesis. Yield per recruit to the surface fishery would increase by about 30% if the longline fishery were eliminated under high input F and the 50: 50 hypothesis and 22%

under the BEH hypothesis. Thus, the nature of age specific sex ratio has a greater effect on the relative success of the longline fishery than on the relative success of the surface fishery. The curves for a longline fishery in the presence of a surface fishery are dome-shaped (Figure 11), while the curves in the absence of a surface fishery are not (Figure 12). This points out the importance of not treating the two fisheries as separate entities unless it is shown that they exploit separate stocks.

At the current size of recruitment, estimates of stock fecundity (egg production per recruit) relative to an unfished stock as a function of fishing effort (Figure 13), are considerably effected by the choice of fecundity index and sex ratio hypothesis but only slightly effected by the choice of input F. At the current level of fishing effort under high input F and 50:50 hypotheses, the relative fecundity is 0.28 when the fecundity index I is used and 0.39 when fecundity index II is used. Under the HIGH M hypothesis, relative fecundity is 0.55 when fecundity index I is used and 0.61 when fecundity index II is used. Thus, at the present level of fishing effort the choice of fecundity index has a 10 to 30% effect on estimates of relative fecundity, while the choice of sex ratio hypothesis has a 30 to 50% effect. The two choices, fecundity index and sex ratio hypothesis, also have considerable effect on relative fecundity at the current level of fishing when it is plotted as a function of size at recruitment (Figure 14).

The relationship between stock fecundity and recruitment has not been demonstrated for any tuna. As shown above, one of the difficulties in demonstrating such a relationship is obtaining a reasonably accurate estimate of stock fecundity. Even if stock fecundity could be accurately determined the recruitment process is likely to be so complex that much more research would be required before a reliable predictor of recruitment could be developed.

It is interesting to note that similar estimates of yield per recruit and relative fecundity are obtained under the HIGH M and BEH hypothesis. Thus it appears that research should be directed towards determining whether or not the 50:50 hypothesis or one of the other two are valid rather than distinguishing between the HIGH M and BEH hypotheses. This should be a fairly simple matter, which would only require a very careful examination of gonad samples of large tunas taken from landed fish. The choice of fecundity index is also of significance for estimating relative fecundity. The difference between the two indices is mainly caused by different maturity schedules (Hayasi et al, 1972). The surface-caught fish appeared to mature at an earlier age than longline-caught fish. This could be an artifact related to the phenomenon noted by Hisada (1973); i.e., mature fish tend to prefer warm water. It should also be a fairly simple matter to determine the cause of the difference between the two indices.

# A SIMULATION MODEL OF PATTERNS OF DISPERSAL AND RECRUITMENT OF YELLOWFIN

Factors that could cause groups of tuna not to be available to all components of a fishery include non-random movements, slow random movements, and recruitment that is non-random in a geographical sense.

Extensive tagging experiments have not produced any clear-cut evidence of a definite migration pattern for yellowfin in the eastern Pacific. Bayliff and Rothschild (1974) recently found evidence both for random dispersal and for directed movements. They were not able to remove the effects of lack of fishing effort in some time-area strata and the coastal boundary on their data. The evidence for directed movements indicated that such movements were generally parallel to the coast. This suggests that the coast influenced their results. Fink and Bayliff (1970), in a synthesis of extensive tagging data, proposed that recruitment to the nearshore surface fishery is not random in a geographical sense, but tends to take place off of Mexico and in the Gulf of Panama.

With the above results in mind, we developed a computer simulation model to examine the inter-relationships of:

1) patterns of movement of fish,
2) patterns of recruitment (i.e. by area), and
3) fishing strategy for two gear types (surface and longline) fishing alone or together on the same population.

The model is general in that it allows the users to specify the nature of the movements, the locations of recruitment and the parameters of growth, and natural and/or fishing mortality.

We represented a hypothetical ocean with the grid shown in Figure 15. The number of fish in each cell at time t is given by the vector

$$N_t = AS_tN_{t-1} \tag{4}$$

Where $N_t$(112 x 1) has elements $(n_i)_t$ equal to the number of fish in cell i at time t, $S_t$(112 x 112) is a diagonal matrix with elements $(s_{ii})_t$ equal to the total survival of fish in cell i from time t - 1 to time t, A(112 x 112) is a probability transfer matrix with elements $(a_{ij})$ equal to the probability of a fish in cell j moving to cell i and where $N_o$(112 x 1) has elements $(n_i)_o$ equal to the number of recruits in cell i.

For our work we specified A, the transfer matrix, by the assumption that for any cell, the probabilities of fish remaining stationary and moving to each of eight adjacent cells is the same, i.e. 1/9. Any other transfer has zero probability. This general rule is modified as follows:

1) Probabilities of remaining stationary in cells imposing on shore are augmented by the sum of those probabilities which would otherwise fall on land. The probability of falling on land is zero.

2) Probabilities projecting beyond the northern and southern edges are absorbed on the boundaries.

3) Probabilities of remaining stationary on the western edge are augmented by the probability of returning from beyond the boundary in a single cycle. The remainder of the fish that move beyond the western boundary are lost to the system.

4) In cells of rows 2 and 7, probabilities of moving towards rows 1 and 8 are decreased by half with the probability of remaining stationary increased by a like amount.

The speed of dispersion is controlled both by A and number of cycles per year. We used four cycles per year for this study, which seemed reasonable based on the results shown in Bayliff and Rothschild (1974).

Two alternative recruitment models were examined. For the first, denoted as inshore recruitment, recruits are divided equally among the five cells 51, 52, 69, 83, and 84, which resemble the recruitment areas proposed by Fink and Bayliff (1970). For the other alternative, denoted as uniform recruitment, recruits are divided equally among all cells except those on the boundaries or on land. Total recruitment is 100 fish. We assumed 1) that fish are 1 year old when recruited, 2) growth proceeds according to the von Bertalanffy curve of LeGuen and Sakagawa (1973), and 3) the coefficient of instantaneous natural mortality is 0.8 on an annual basis and is independent of time and location. Fish older than 6 years (175 cm) were removed from the system. Consequently, under constant conditions the fishery reaches equilibrium in 5 years. The system was always run for 5 years before an experiment was run.

We first examined the effects of location, dispersal, and location of recruitment on age distribution and the resulting apparent rate of natural mortality obtained from unbiased samples from an unfished population. Mortality was estimated with the standard linear regression model from the age distribution of fish in each cell. The regression technique assumes that mortality is constant after full recruitment and we assumed that the modal age represents first age of full recruitment. The results reveal that M is usually overestimated (Figure 16). Estimates of M tend to be relatively high near areas of spawning with inshore recruitment. In the case of uniform recruitment, estimates of M tend to be highest on the western boundary where fish are lost to the system. Modal age tends to increase in a westerly direction for inshore recruitment and stay relatively constant for uniform recruitment (Figure 16). It is interesting to note that the modal size of actual catches of surface-caught yellowfin in the eastern Pacific also increases in a westerly direction (Figure 17). Although the surface fishery probably does not take an unbiased sample of the size distribution of the population, the data are suggestive of reduced recruitment in the western areas.

We simulated a 20-year hypothetical yellowfin fishery to examine interactions among a longline fishery, inshore surface fishery, ocean-wide surface fishery, and ocean-wide surface fishery that does not heavily exploit young fish, as follows:

1) For the first 5 years only longliners fished and only in rows 5 to 8.

2) For the next 5 years this longline fishery was augmented with surface gear on all cells adjacent to the coast.

3) Next, exploitation by the surface gear was expanded to include all areas for 5 years.

4) Finally, for the last 5 years, age specific surface fishing mortality was reduced by 75% for fish less than 2.5 years of age, because much of the surface catch of yellowfin in offshore areas of the eastern Pacific comes from schools associated with porpoise. Typically, porpoise schools contain few yellowfin less than 2.5 years of age.

Age specific fishing mortality rates similar to those estimated by Lenarz et al (1974) for the Atlantic yellowfin fishery were used (Table 5). The Ricker yield equation was used to calculate yield for each time-area strata. To save space in this section, we refer to yield per recruit as either yield or catch.

Total yields were calculated and are shown in Figure 18. Yields are quite similar for both recruitment models except near shore where yield was considerably higher for the inshore recruitment model than for the uniform recruitment model. The difference in yield between the two models decreases slightly as time increases. Yield closely approached equilibrium yield within 3 years after a change was made in the fishery. Total equilibrium yield with an inshore surface fishery and longline fishery was about 17% higher than with a longline fishery alone, 54% higher with a uniform surface fishery than with only a longline and inshore surface fishery, and increased by 9% when F for small fish was reduced by 75%. Under the assumption that the catchability coefficient is independent of area, the surface fishery increased its equilibrium yield about fourfold by increasing its effort about twelvefold when it expanded into offshore waters. The same action decreased yield to the longliners by about 55%.

Table 5. Estimates of values of age specific F on an annual basis.

| Age (years) | Longline gear | Surface gear | Surface gear with reduced F |
|---|---|---|---|
| 1.0 | 0.00 | 0.30 | 0.08 |
| 1.5 | 0.00 | 0.30 | 0.08 |
| 2.0 | 0.05 | 0.22 | 0.06 |
| 2.5 | 0.15 | 0.20 | 0.20 |
| 3.0 | 0.25 | 0.18 | 0.18 |
| 3.5 | 0.35 | 0.30 | 0.30 |
| 4.0 | 0.45 | 0.35 | 0.35 |
| 4.5 | 0.40 | 0.42 | 0.42 |
| 5.0 | 0.40 | 0.27 | 0.27 |
| 5.5 | 0.20 | 0.20 | 0.20 |
| 6.0 | 0.05 | 0.15 | 0.15 |

We next examined the potential yield to longliners in rows 5, 6, 7, and 8 by starting a longline fishery with age specific F vector multiplied by the scalar 0.3 and then multiplying by 1.3 each year afterwards. Yield appears to approach as asymptote of about 6 kg for inshore recruitment and 5 kg for uniform recruitment (Figure 18). The reduction in catch per effort by fishing is not significantly effected by choice of recruitment model. Even though catch per effort at high levels of effort was only about 20% of that at the beginning of exploitation, over-fishing in a yield-per-recruit sense did not occur. Average size of fish in the catch was not significantly affected by the recruitment model and decreased from about 50 to 30 kg with increased fishing effort (Figure 19).

A simulation for an inshore surface fishery indicated an asymptotic production curve with a maximum yield of about 1.4 kg for uniform recruitment and 2.2 kg for inshore recruitment (Figure 20). Catch per effort was reduced by about 75% under both alternatives. The ratio of maximum yield for a longline fishery to an inshore surface fishery was about 2.7 for inshore recruitment and 3.4 for uniform recruitment. Average size of fish in the catch was about 2 kg higher for uniform recruitment than for inshore recruitment and decreased from 16 to 18 kg to 8 to 11 kg with increased fishing effort (Figure 20).

Simulation of a uniform surface fishery revealed that choice of recruitment model had an insignificant effect on catch, catch per effort, and average size of catch, except that catch per effort in the near shore area was relatively high for inshore recruitment (Figure 21). A 75% reduction in F for fish less than 2.5 years old had considerable effect on the results. Maximum yield increased from about 5 to 6.5 kg when F was reduced. Both yield curves are dome-shaped. Catch per effort became relatively higher at high levels of effort when F was reduced. As expected, average size was considerably higher for reduced F.

With inshore recruitment, maximum yield changes from about 2.2 kg for an inshore fishery (Figure 20) to about 5.1 for a uniform fishery (Figure 21). With uniform recruitment, maximum yield changes from about 1.4 kg for an inshore fishery to about 5 kg for a uniform fishery.

The results of this section indicate that the pattern of recruitment is primarily of interest for examining the potential of a nearshore surface fishery to a surface fishery that exploits the entire area or a longline fishery. The presence of some small yellowfin in length-frequency data from the eastern tropical Pacific fishery (Figure 17) reveals that some recruitment occurs offshore. Apparently recruits are not highly available to surface fishing offshore because most yellowfin are caught in schools associated with porpoise. Such schools normally contain only low percentages of small yellowfin. A well designed tagging study would provide estimates of the exploitation rate by size for yellowfin in the offshore areas. These estimates would be based on the assumption that tagged fish have the same vulnerability to fishing as untagged fish. Since the small yellowfin that are captured and tagged in an offshore area may be exhibiting atypical schooling behavior at the time of capture, it would be desirable to capture small yellowfin for tagging by unconventional methods. Trolling would allow capture of unschooled yellowfin, but would be an inefficient procedure of capture. Until the pattern of recruitment is determined it will be necessary to continue estimations of relative production to longliners, inshore surface gear, and offshore surface gears in an empirical fashion.

We only examined one reasonable example of an infinite number of configurations of the transfer matrix A and number of cycles per year. Further use of the model should include a sensitivity analysis of the results to choice of A and number of cycles per year.

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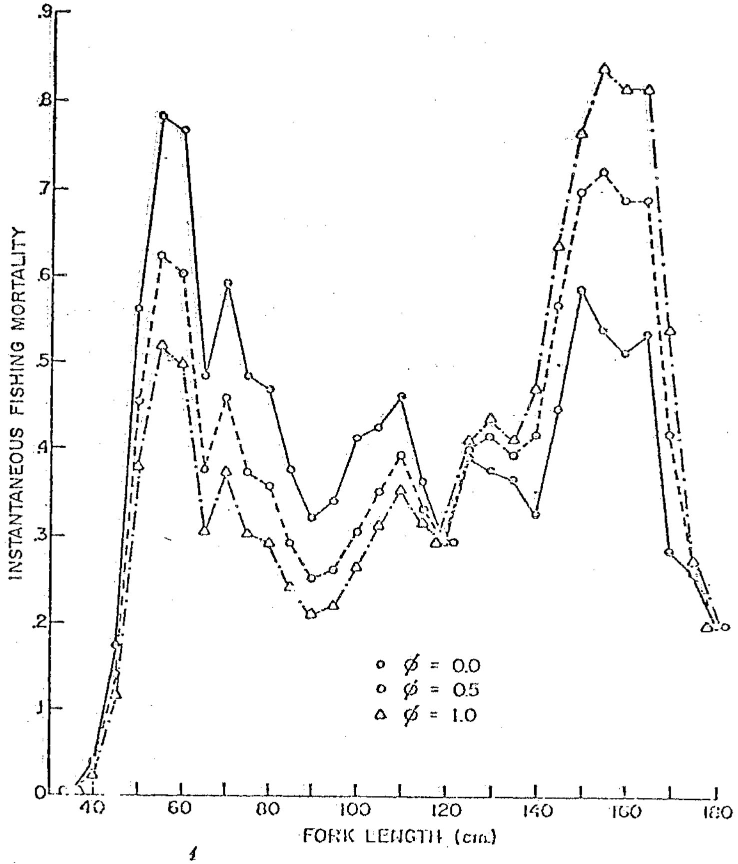


Figure 1. Estimates of size specific fishing mortality of Atlantic yellowfin tuna as a function of proportion of catch (∅) by longline fishery that comes from stock(s) exploited by surface fishery.

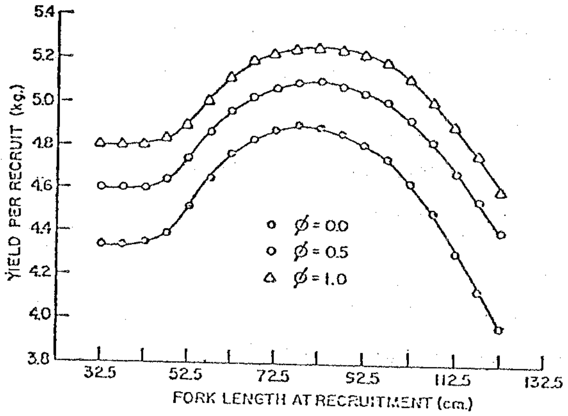


Figure 2. Yield per recruit (kg) of Atlantic yellowfin tuna as a function of size at recruitment and proportion of catch (∅) by longline fishery that comes from stock(s) exploited by surface fishery. Fishing mortality is equal to the present value.

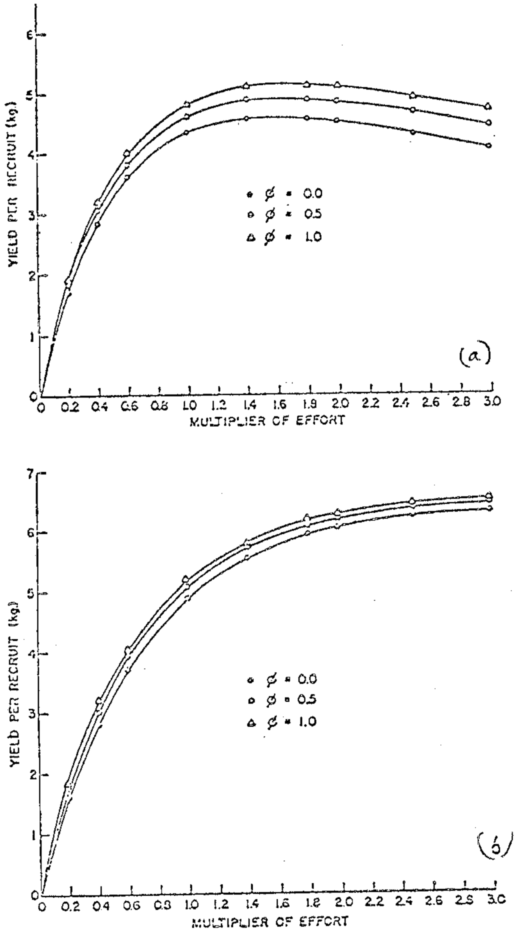


Figure 3. Yield per recruit of Atlantic yellowfin tuna as a function of fishing effort and proportion of catch (ø) by longline fishery that comes from stock(s) exploited by surface fishery: (a) size at recruitment is 32.5 cm, (b) size at recruitment is 77 cm.

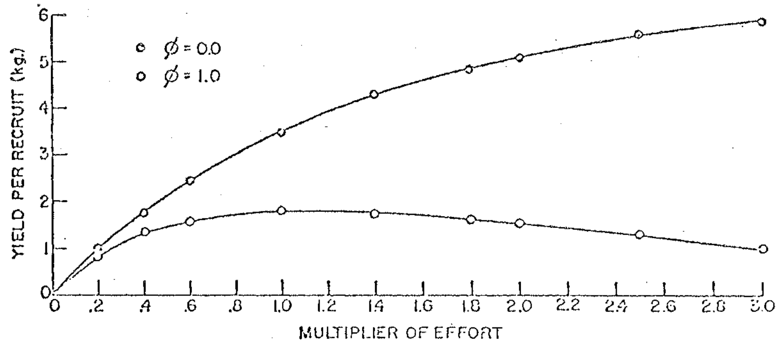


Figure 4. Estimates of yield per recruit of Atlantic yellowfin tuna to the longline fishery as a function of effort and presence (ø = 1.0) or absence (ø = 0.0) of surface fishery.

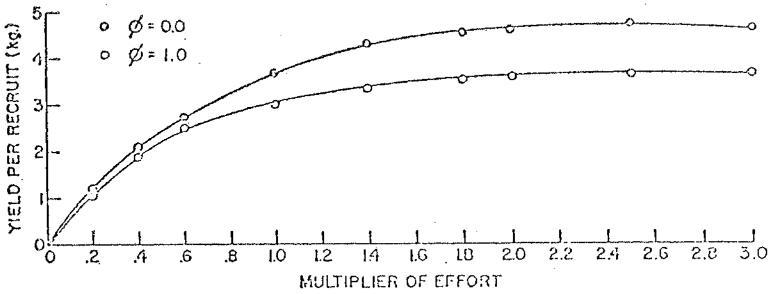


Figure 5. Estimates of yield per recruit of Atlantic yellowfin tuna to the surface fishery as a function of effort and presence (ø = 1.0) or absence (ø = 0.0) of longline fishery.

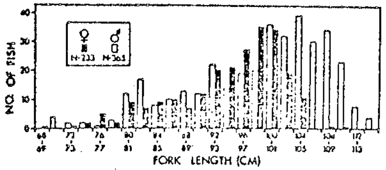


Figure 6. Length-frequency distribution of 598 male and female albacore measured at canneries in Puerto Rica from December 1969 to September 1970. All were caught in the Atlantic by longline gear.

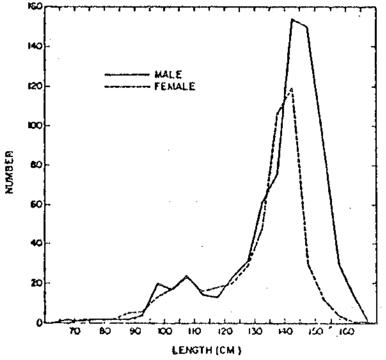


Figure 7. Length distribution by sex of longline-caught yellowfin tuna in central Pacific Ocean (Murphy and Shomura, 1972).

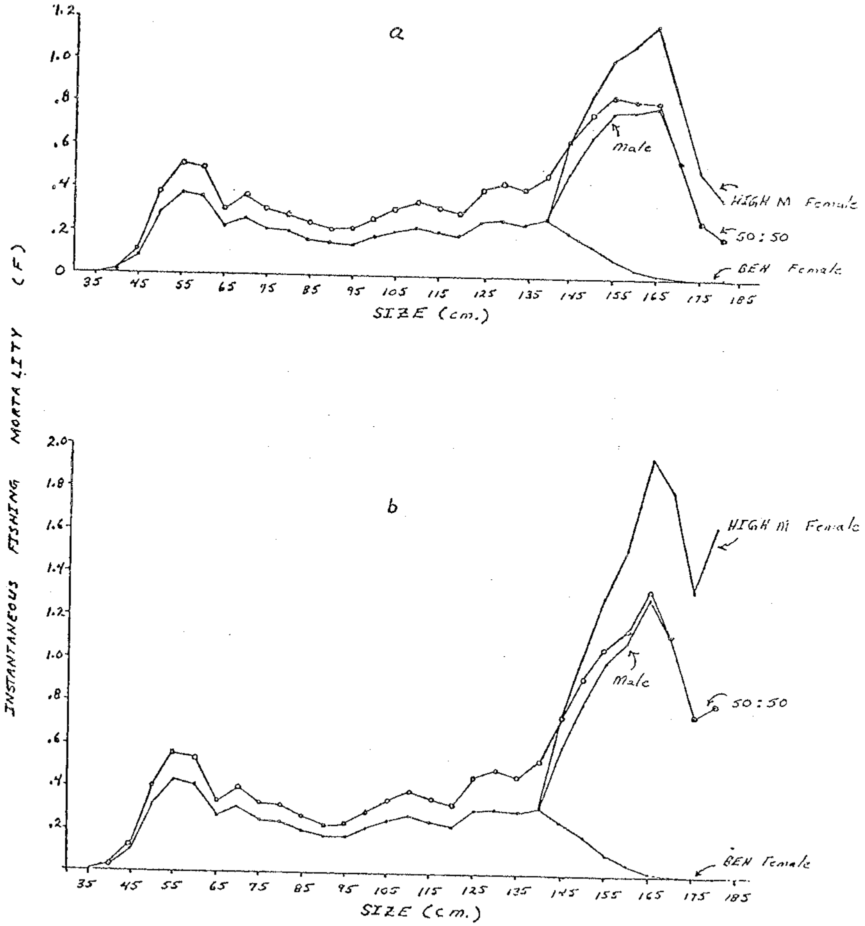


Figure 8. Estimates of size specific coefficient of instantaneous fishing mortality on an annual basis (F) for Atlantic yellowfin tuna: (a) low input F, (b) high input F.

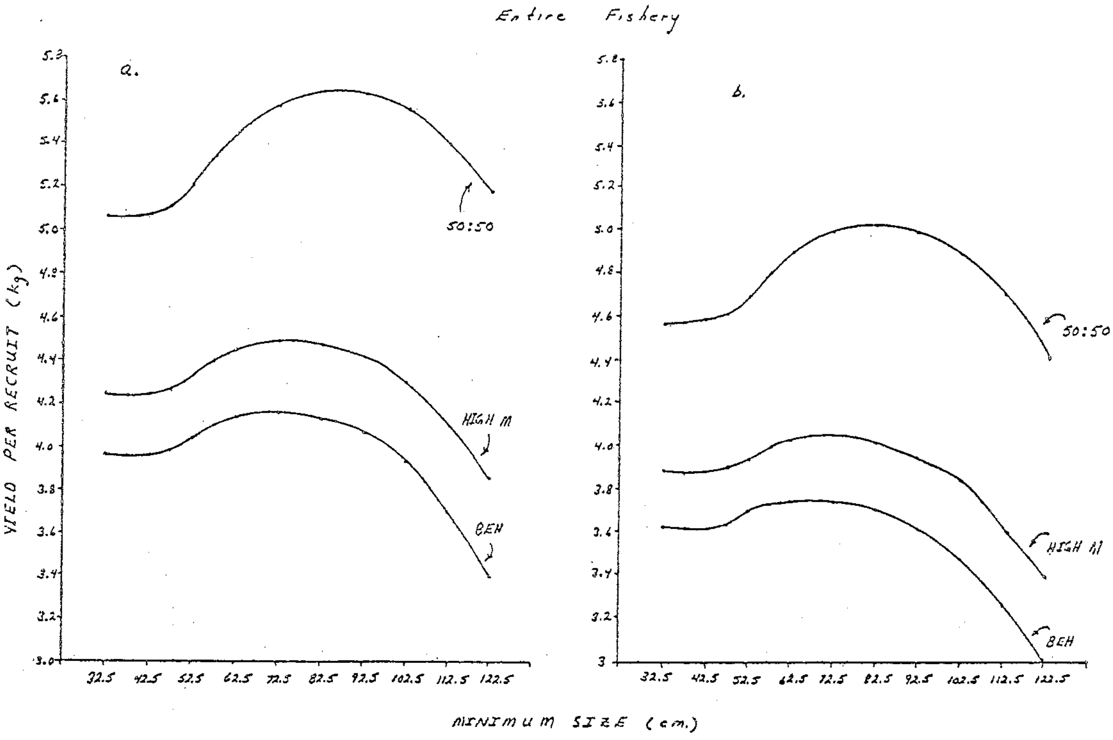


Figure 10. Estimates of yield per recruit of Atlantic yellowfin tuna at current level of fishing as a function of size at recruitment: (a) high input F, (b) low input F.

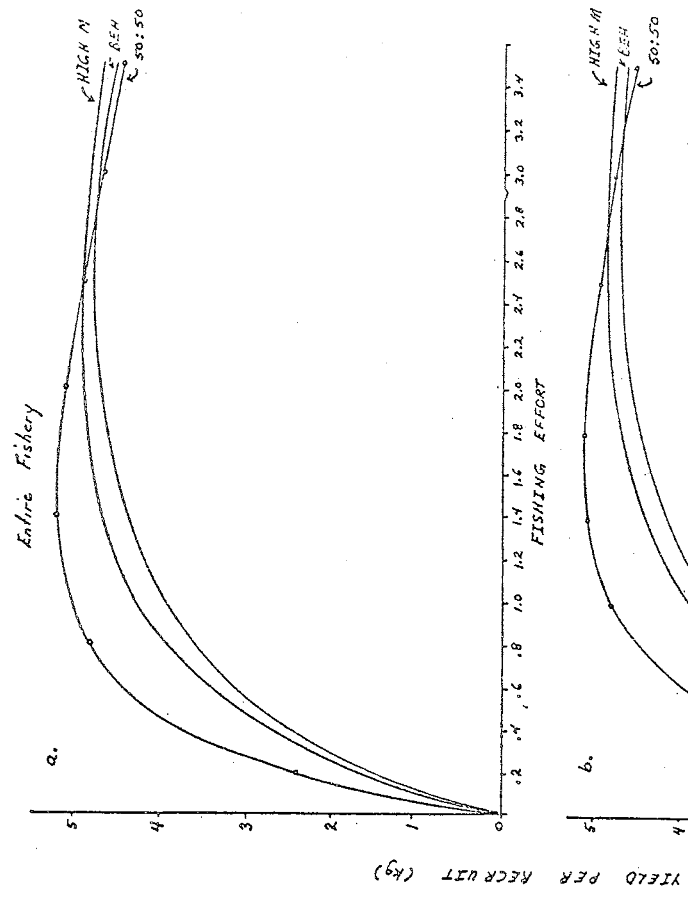


Figure 9. Estimates of yield per recruit of Atlantic yellowfin tuna at present size of recruitment as a function of fishing effort and sex hypothesis: (a) high input F, (b) low input F.

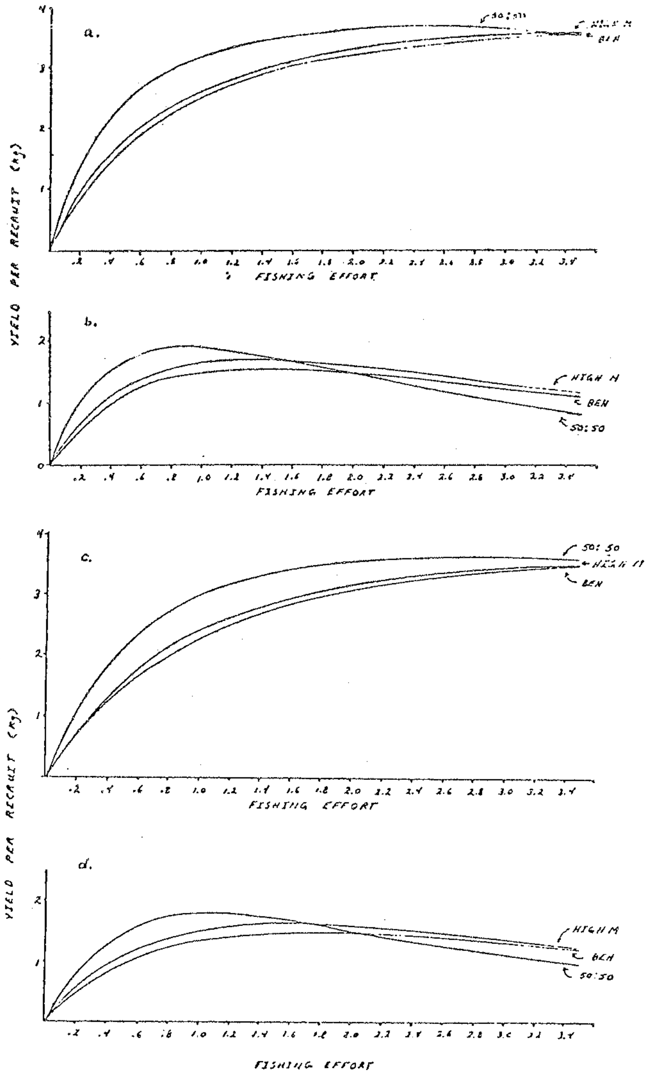


Figure 11. Estimates of yield per recruit of Atlantic tuna when both gears fish at current size of recruitment as a function of sex ratio hypothesis, fishing effort, and gear: (a) surface gear with high input F, (b) longline gear with high input F, (c) surface gear with low input F, and (d) longline gear with low input F.

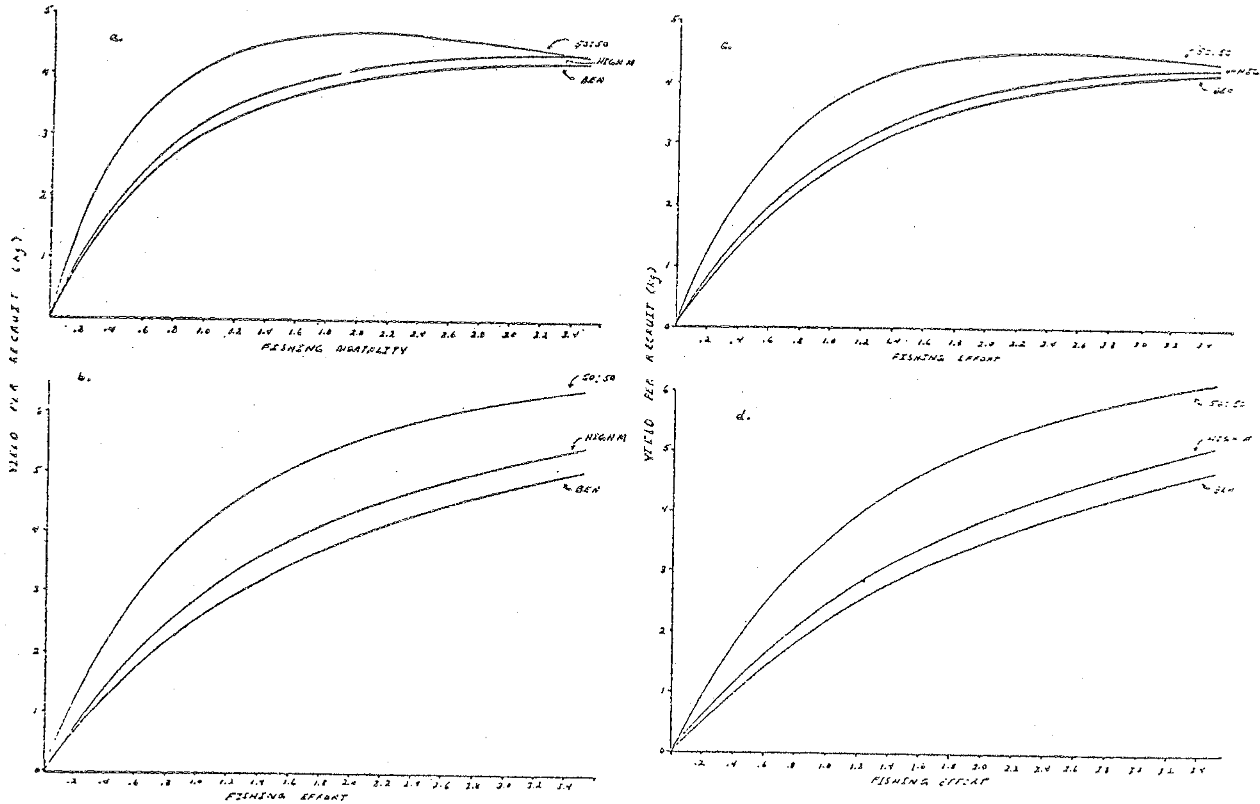


Figure 12. Estimates of yield per recruit at current size at recruitment as a function of fishing effort, sex ratio hypothesis, and fishing gear when only one gear is fishing: (a) high input F and surface gear, (b) high input F and longline gear, (c) low input F and surface gear, and (d) low input F and longline gear.

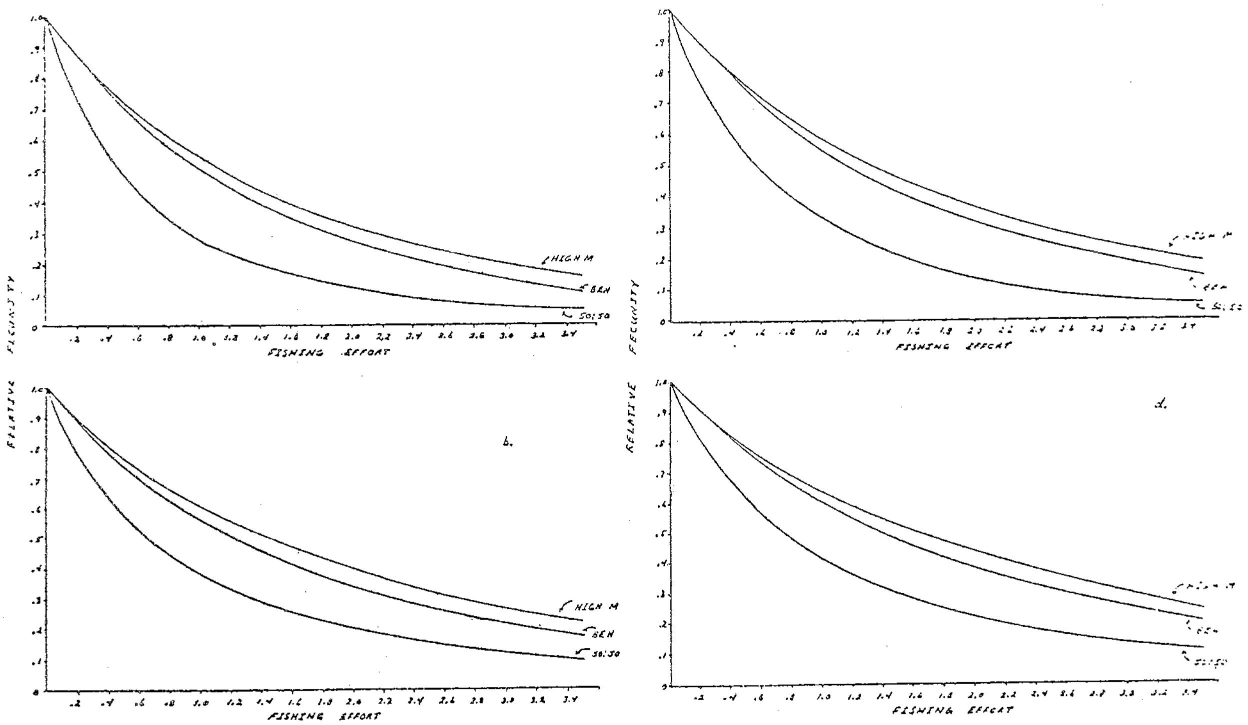


Figure 13. Estimates of relative stock fecundity at current size at recruitment as a function of fishing effort, fecundity index, and sex ratio hypothesis: (a) high input F and fecundity index I, (b) high input F and fecundity index II, (c) low input F and fecundity index I, and (d) low input F and fecundity index II.

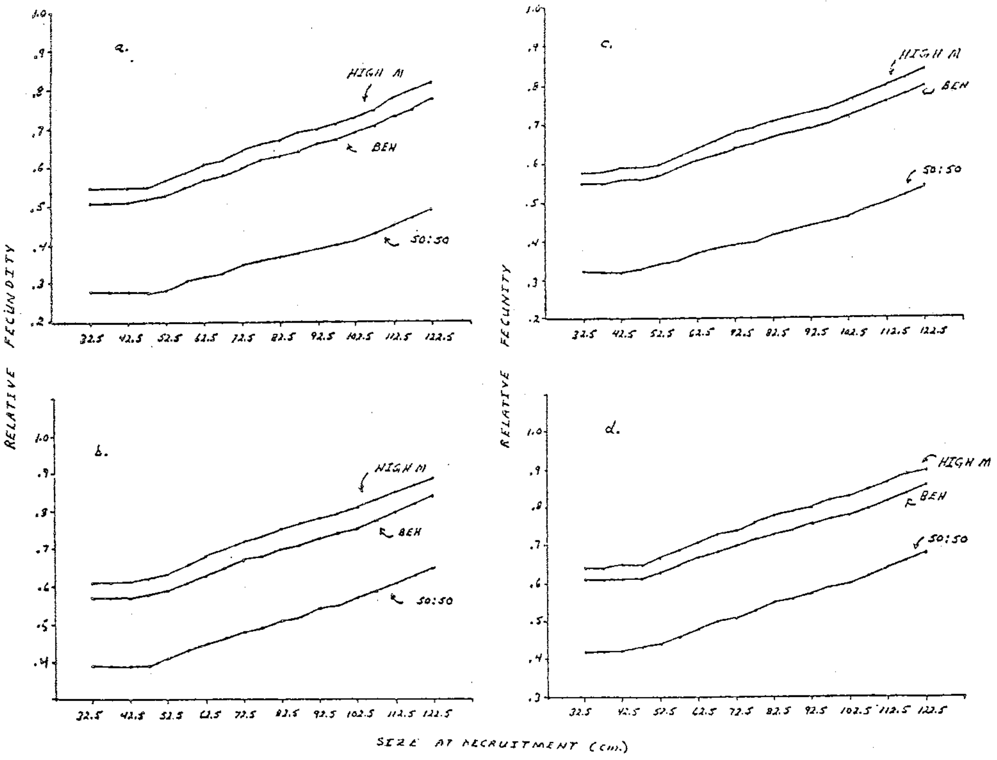
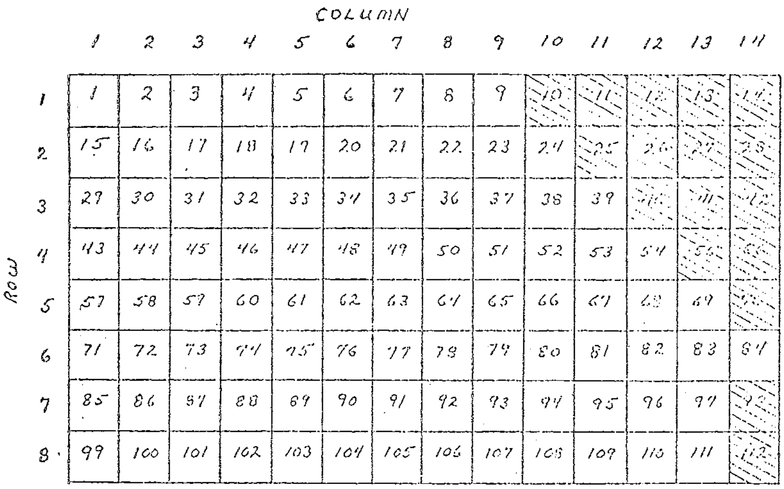


Figure 14. Estimates of relative stock fecundity at current level of fishing as function of size at recruitment, fecundity index, and sex ratio hypothesis: (a) high input F and fecundity index I, (b) high input F and fecundity index II, (c) low input F and fecundity index I, and (d) low input F and fecundity index II.



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 2 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
| 3 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 |
| 4 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 |
| 5 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 |
| 6 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 |
| 7 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
| 8 | 99 | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 |

Figure 15. Map of hypothetical ocean. Each cell represents a 5° square. Hatched cells represent land. Column 1 is western boundary. Row 1 is northern boundary and row 8 is southern boundary.

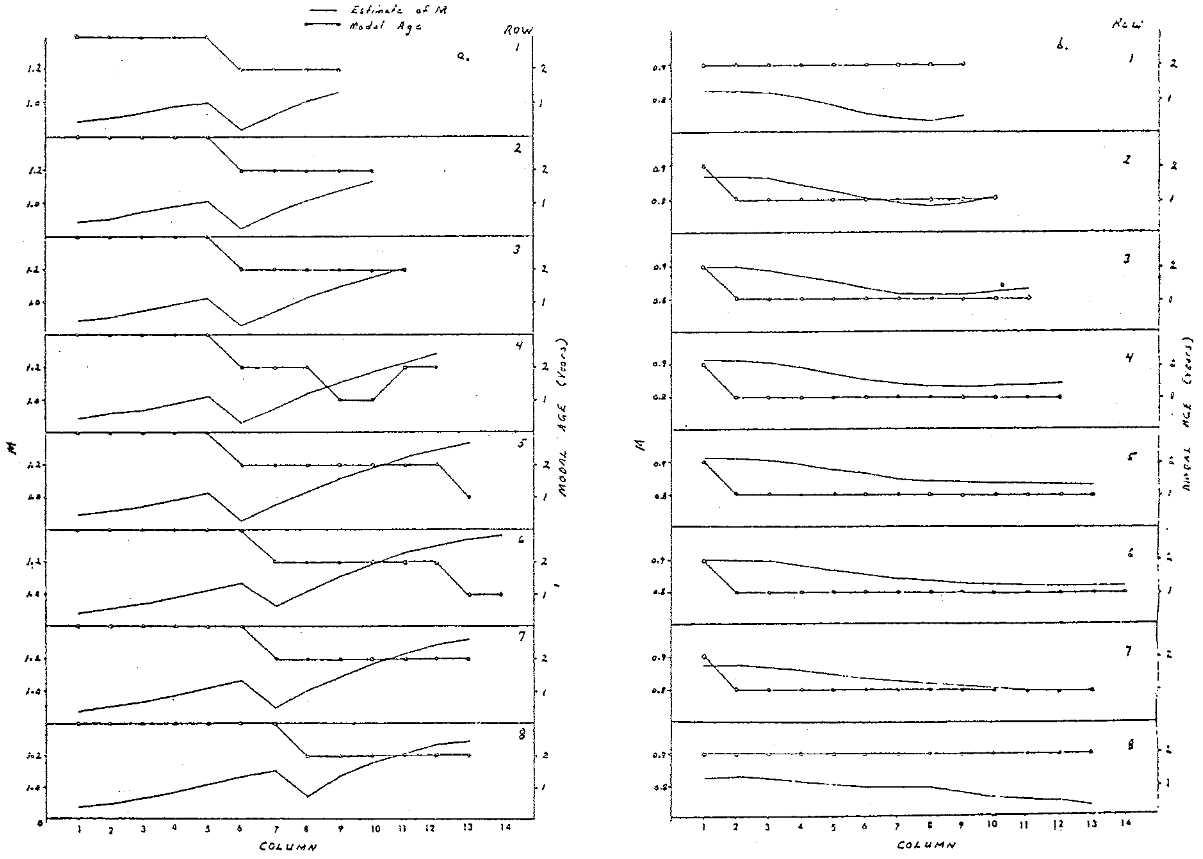


Figure 16. Estimates of coefficient of instantaneous natural mortality on an annual basis (M) and modal age of yellowfin by row and column: (a) inshore recruitment, and (b) uniform recruitment.

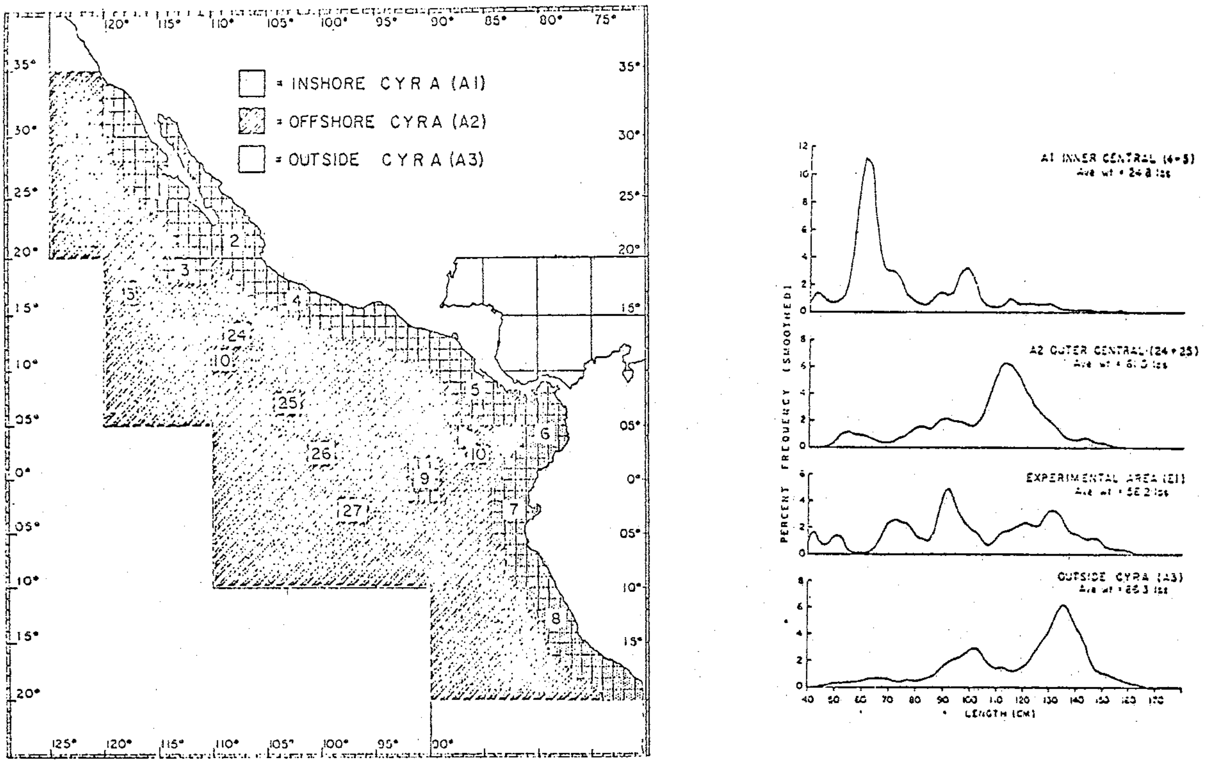


Figure 17. Taken from IATTC (1974): (a) the eastern tropical Pacific Ocean showing areas A1, A2, and A3. The numbers within the areas designate sub-areas used for size composition studies, and (b) length-frequency distribution of yellowfin tuna in the inner area (areas 4 and 5), the outer area (areas 24 and 25) of the central region of the CYRA (Commission Yellowfin Regulatory Area), in the experimental area (E1) and in the area to the west of the CYRA (A3).

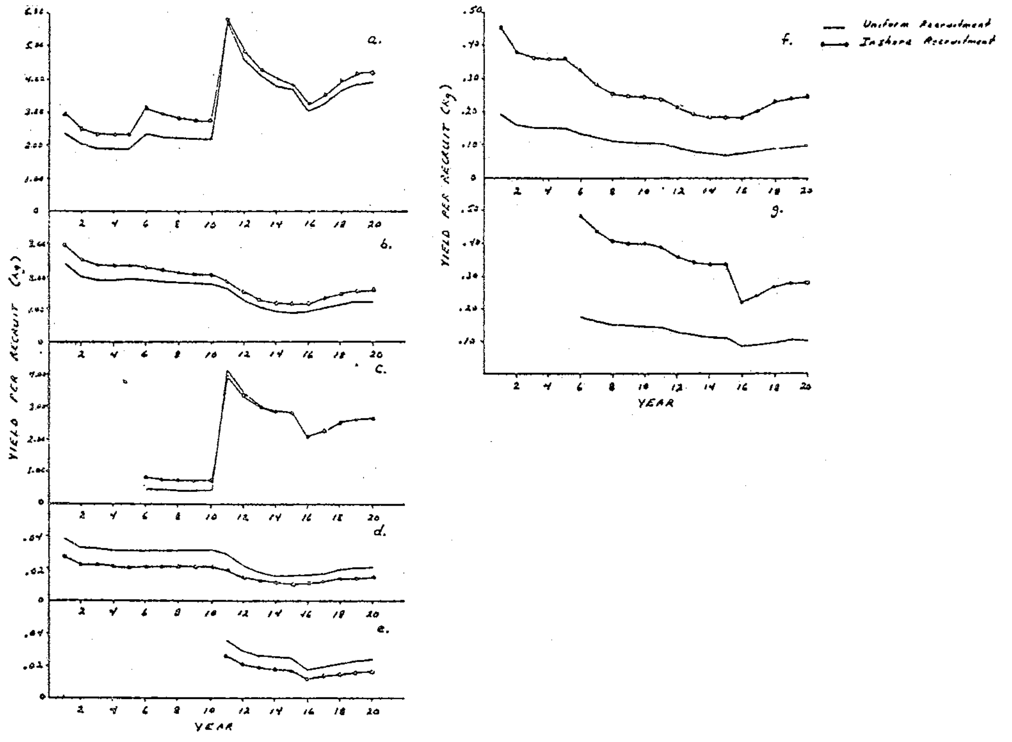


Figure 18. Yield per recruit of hypothetical yellowfin fishery: (a) total, (b) longliners in all areas, (c) surface gear in all areas, (d) longliners in cells 71 and 85, (e) surface gear in cells 71 and 85, (f) longliners in cells 69, 84, and 97, and (g) surface gear in cells 69, 84, and 97.

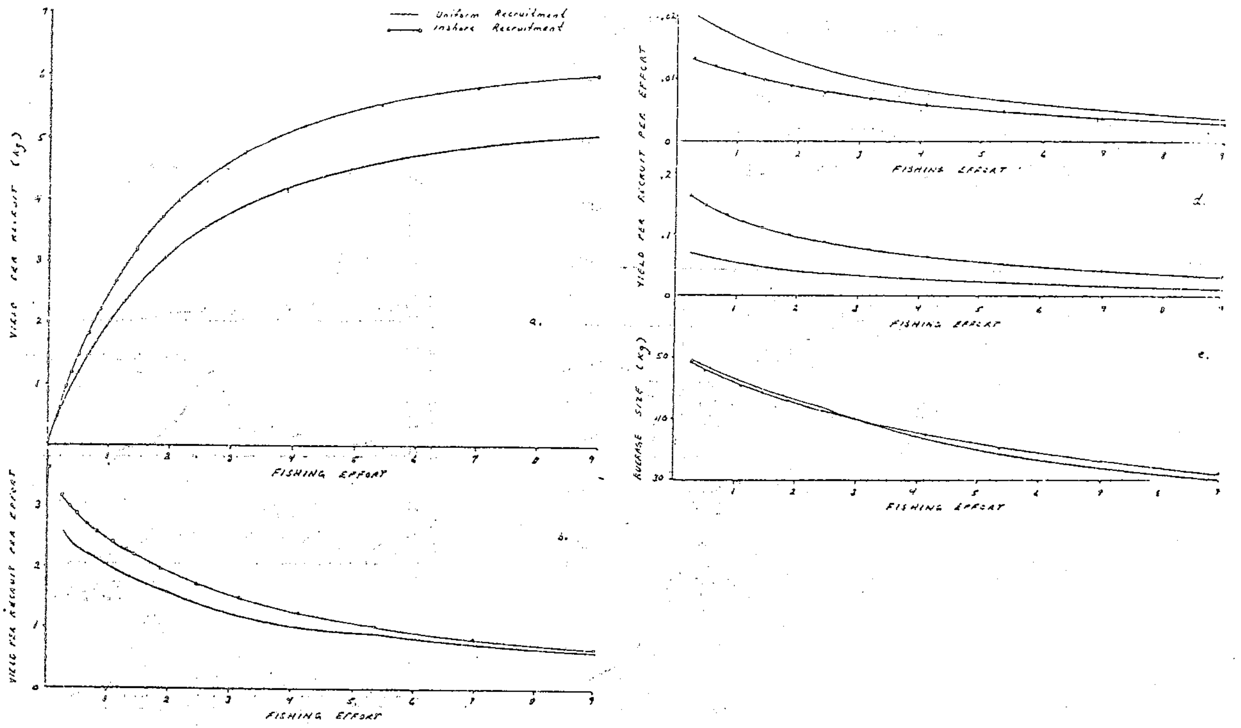


Figure 19. Yield per recruit, yield per recruit per effort, and average size of catch for hypothetical longline fishery: (a) total yield per recruit, (b) total yield per recruit per effort, (c) yield per recruit per effort in cells 71 and 85, (d) yield per recruit per effort in cells 69, 84, and 97, and (c) average size.

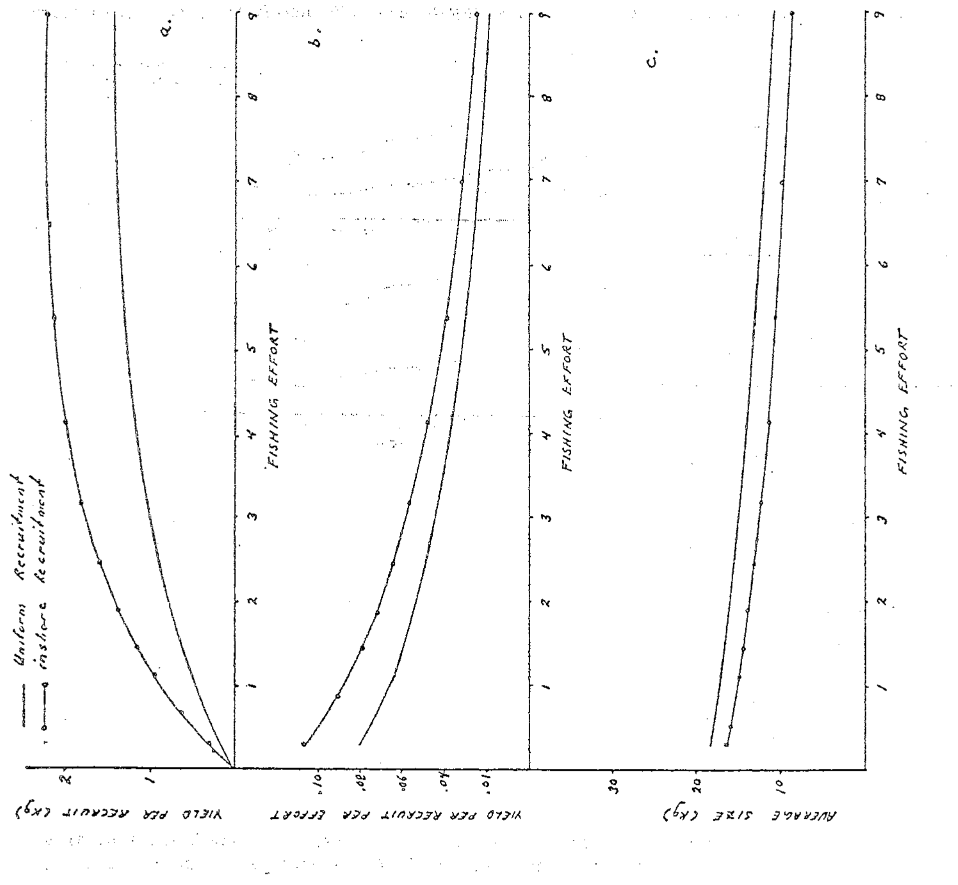


Figure 20. Yield per recruit, yield per recruit per effort, and average size of catch for hypothetical inshore surface fishery: (a) yield per recruit, (b) yield per recruit per effort, and (c) average size of catch.

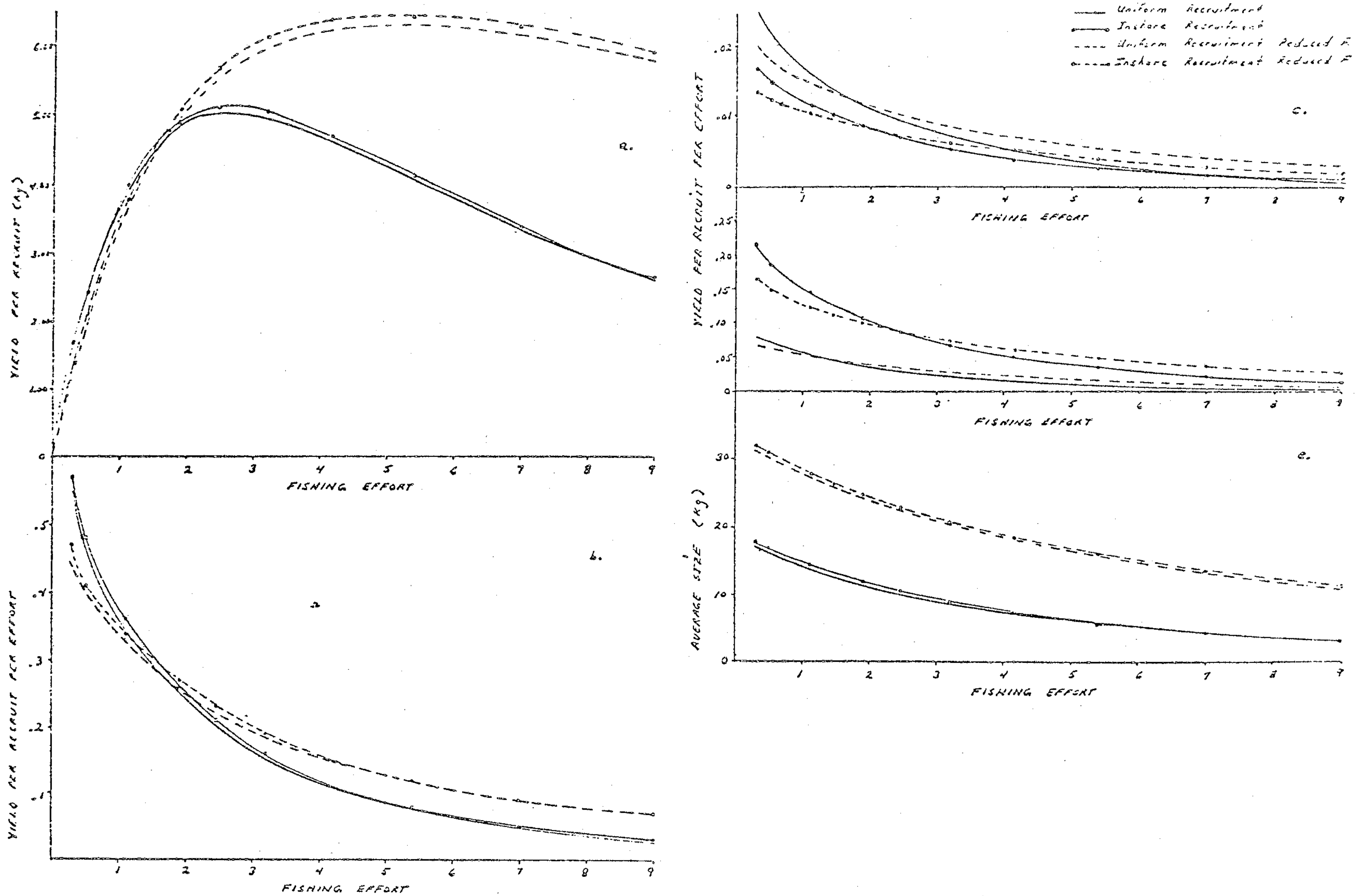


Figure 21. Yield per recruit, yield per recruit per effort, and average size of catch for hypothetical uniform surface fishery: (a) yield per recruit, (b) yield per recruit per effort, (c) yield per recruit per effort in cells 71 and 85, (d) yield per recruit per effort in cells 69, 84, and 97, and (e) average size of catch.