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Biological Analysis of the Northern Anchovy Fishery System

by

M. F. Tillman
G. J. Paulik

University of Washington

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CONFIGURATION OF THE SYSTEM

The fishery for northern anchovy does not operate exclusively upon that species but rather is a multi-species system which involves a variety of harvesters, and products. Figure 1 indicates the logical relationships which historically have evolved within this system. The three fleets involved are actually remnants of the once great Pacific sardine fishery. The four stocks taken by the system might in some regards be considered substitute sardines. The locations indicated refer to the two northern anchovy quota areas which have been levied by the California Department of Fish and Game; the dividing line between the two occurs at Point Conception, California.

The Monterey sub-fishery has been a failing enterprise for several seasons, and according to California Department of Fish and Game personnel, will be an insignificant entity during the present and future seasons. Processor facilities are reportedly in a serious state of disrepair and likely will be closed. The fleet is composed of seven of the oldest and smallest vessels of the entire system (Messersmith, 1969); these have been concerned only with northern anchovy, and once the Monterey processor closes they will no longer have a market for their catches. For these reasons, the Monterey sub-fishery has been removed from further consideration, thus leading in part to the simplified system of Figure 2.

The live-bait sub-fishery for anchovy has had a consistently large economic impact despite its small size. The total fishery, primarily confined to Southern California, takes only 4,000-7,000 tons annually but averages sales of $1.5 million per year (Baxter, 1967). The real value of the live-bait fishery, however, lies in its contribution to the recreational activities of sport fishermen. The bait subsystem accordingly is worth much more than the value of the bait alone, but we are presently incapable of measuring its total economic contribution or to assess how that contribution might be affected by other segments of the system. Given this evaluation problem and the fact that the live-bait catch of anchovy is biologically insignificant and unlikely to grow much larger in the future, this subsystem also has been removed from further consideration. However, due to its considerable political clout (sportsmen and bait fishermen are allied to sponsor state legislation crippling commercial development of anchovies), the bait sub-fishery must still be considered an external or environmental force of great import to the remaining system.

The Los Angeles or Wetfish sub-fishery has evolved into the largest and most economically significant segment of the total anchovy system. Yet in its present configuration, this sub-fishery is at best only a marginal operation. The four plants located at Terminal Island are primarily interested in processing tuna, supplies of which are purchased mainly from the high seas tuna fleet. The landings of bluefin tuna, Pacific bonito, and jack mackerel supplied by the small Wetfish fleet are used simply to augment primary sources during the off-season or at times of low availability. These four plants also reduce the offal of the above species into meal and oil; the landings of anchovies which they purchase from the Wetfish fleet again are used merely to augment the amounts of offal available. So the Wetfish fleet presently acts as an augmenter of raw materials rather than as the primary source, and, due to current price-cost situations, the Terminal Island plants would rather produce canned fish for human use and pet food than reduce anchovies into meal and oil. Should a change in emphasis occur, though, considerable renovation of the current reduction facilities would probably be required since present total capacity is only 1,200 tons per day. At this level processors could handle only one-half the capacity of the present highly inadequate Wetfish fleet (Frey, 1971).

The Wetfish fleet is presently composed of 30 purse seiners: 20 averaging 110 tons capacity, and 10 averaging 45 tons. During recent seasons, a division of labor has occurred between the two segments of the fleet, leading to the representation depicted in Figure 2. The small vessel fleet has been capturing jack mackerel, and the large vessel fleet has been operating on anchovies, taking jack mackerel during anchovy closures. Both fleets will take bluefin tuna or bonito as targets of opportunity if their primary targets are not encountered during a trip. Bluefin tuna are especially valued because of the high prices they bring, and occasional bouts of bluefin tuna fever occur during July-August when the species migrate through the area. Catches of these two alternate species have not comprised significant proportions of each vessel's total annual landings, however. This fact coupled with a lack of quantitative biological knowledge led to their being omitted from the system. (This in turn led to dropping canned fish for human use from Figure 2, since jack mackerel currently is prepared only as pet food because of a DDT problem).

The California Department of Fish and Game is presently the only regulator within the system. Current regulations affect the system only with respect to anchovy. For this species catch quotas are set by area (100 thousand tons in the southern area, 10 thousand in the northern), specific areas are closed to fishing (none within 3 miles of shore), seasons are fixed (15 September - 15 May), and a minimum size limit has been levied (10.8 cm TL), although not enforced (Messersmith, ibid.). The summer closure and low quotas have been levied as the result of extensive lobbying by the aforementioned sport and bait-fishery interests. Processors have indicated that these two regulations, particularly the low quotas, are significant barriers to full economic development of the northern anchovy resource (Frey, ibid.). This is a position which shall be examined in the following sections of this report.

THE NORTHERN ANCHOVY BIOLOGICAL SECTOR

The California Current system is the world's most well-known eastern boundary current upwelling system. The development and later collapse of the California sardine fishery generated scientific investigations that have continued until the present. In the late '30's and early '40's, annual catches of over 600,000 metric tons of sardine were common. After violent oscillations in the late '40's, the catches in the early '50's dropped in three years from over 350,000 tons to less than 15,000 tons. The scientific documentation of the collapse of the sardine fishery is remarkably complete, yet fishery scientists still argue about the causes; perhaps the definitive autopsy will never be performed. Recruitment failed as the fishery oscillated before finally approaching a new low equilibrium level. About the time of the demise of the sardine populations, anchovy populations in the California Current system increased tremendously. Whether this was a successional replacement phenomenon, or, natural cyclic variation of the dominant species in the California Current, or, simply a coincidental event occurring at the time overfishing stress destroyed the sardines, or, was caused by subtle environmental changes is a matter of conjecture. Older sardines had virtually disappeared and the entire fishery was focused on a few very young year classes. Water temperatures dropped slightly in the system as the sardines began to disappear. Fishery scientists are concerned about this sort of replacement in other upwelling systems, e.g., at present,replacement of the pilchards in the Benguela Current system off South Africa by anchovies may be occurring.

The general productivity of a fish stock is determined by its life history pattern and its absolute abundance. The northern anchovy is a small, short-lived, pelagic, schooling clupeoid ranging from lower Baja California to Vancouver Island, British Columbia, and usually occurs within 20 miles of the coast. Primary centers of abundance are in the California Current system off central and southern California and Baja California. Spawning occurs in huge schools or swarming aggregations and is spread out over virtually the entire year. Pelagic egg and larvae surveys indicate most reproductive activity is concentrated in the offshore areas during winter and spring. There appears to be considerable variability in the peak of the spawning activity in both space and time from year to year. The northern anchovy is an indiscriminate filter feeder. Feeding and growth occur inshore during the late spring, summer and fall months.

Critical components of the life history which affect the stock's productivity and must be considered in any planning analysis of future expansion of the fishery are discussed in detail below. More definitive life history descriptions are given by Baxter (1967); Messersmith, Baxter, and Roedel (1969); and Frey (1971). The discussion below is an attempt to develop a general conceptual framework for determination of parameter values and functional forms for processes in the model and to provide the reader with a general overview of the reliability of our knowledge of various biological processes and parameter values.

The absolute magnitude of the ultimate sustainable catch as well as the manner in which the catch might be expected to expand in response to increased fishing pressure is dependent on a few critical processes and population parameters. Unfortunately these particular parameter values are difficult to estimate precisely and these particular processes are poorly understood. An anchovy stock is a highly dynamic entity continuously generating new biomass by both reproduction and growth; rapid turnover rates make understanding and unraveling the interactions of these ongoing continuous processes a <u>sine</u> <u>quo</u> <u>non</u> for rationale management. The basic mathematical representation of the productivity dynamics of the stock can be described in terms of structure and process. Even for a fish stock as intensively studied as the Peruvian anchoveta (Engraulis ringens) which supports the world's largest single fishery neither the structure nor the critical processes have been defined satisfactorily. The "best" scientific estimates of sustainable yield for the Peruvian system have changed markedly since the fishery developed so rapidly in the late '50's and began to level off in the late '60's. Experts in population dynamics still disagree on the types of models that should be employed to compute maximum sustained yield for the Peruvian anchoveta. While scientists have studied the California system far more intensively than the Peru system, the Peruvian fishery has sampled the anchovy populations by taking annual catches that have been in the vicinity of 11 million metric tons the last few years. These catch data have been subjected to intensive analysis.

Structure and Distribution of the Northern Anchovy Populations

Morphometric evidence, blood type analysis, some tagging, and general biological observations all support the hypothesis that there are three somewhat distinct stocks of anchovy off the west coast of North America. The degree of separateness of these stocks has not been established; however, it is thought that there is rapid intermixing and exchange of animals between all segments within a given stock. Tagging results, for example, indicate anchovy commonly move at rates averaging over 30 miles per day; within the space of a month (a common sampling frequency in this fishery) complete exchange could occur within a stock.

The three stocks inhabit the following areas: (1) from Point Conception north with the northern boundary undefined, (2) from Point Conception southward to approximately Ensenada, Mexico, and (3) south from Ensenada, Mexico to just below Baja, California. The approximate sizes of the standing crops of fishable anchovy in these three areas (from north to south) are: 1, 4-5, and 2 million metric tons. The fishable populations include some one-year-old fish and all fish two years and older, assuming, of course, that the existing ageing techniques are correct. There is an approximate 18° isotherm at about the boundary that separates the southern from central stocks. The central area has been studied intensively and contains the stock that will be treated in this report. Not enough is known about either the northern or the far southern stocks to make any but the grossest recommendations on potential productivity. Also because of the economics of transporting anchovy for long distances, it is most unlikely that boats will operate routinely beyond a 20-30 mile radius of their fishing port. The occasional long trips (over 60 miles) made by bolicheras (seiners) in Peru are a matter of necessity when no fish are available close to the factories. For the North American stocks a comprehensive system of ports is needed before a fishery can be developed to supply meal and oil factories. Lack of ports would certainly hamper any development of the southern stock.

Schooling behavior which reduces catchability is observed during spawning, especially during the winter. Behavioral catchability increases greatly during May through October. Upwelling intensity and oceanographic currents may condition the behavior that determines catchability. In the Peru Current availability varies greatly with the strength of upwelling; intense upwelling in the southern winter scatters the fish and makes them extremely hard to catch.

The natural mortality rate in the virgin stock is of importance for estimating potential productivity. While there is considerable evidence (see below) that the instantaneous natural mortality rate value M is about 1.0 for the northern anchovy, this value is extremely low compared to published estimates of M for other anchovy stocks. Some scientists have estimated higher M's for the California system, e.g., Bayliff (1967) estimated M to be 1.7. The size of M is critical; to maintain stability a stock must replace natural removals. A high rate of natural mortality implies a high turnover rate;

the average age (or average stay in the life state) of a fish is inversely related to the total instantaneous mortality rate. For a fixed standing crop, and all other factors constant, it is generally true that the higher the mortality rate, the greater the stock's ability to produce harvestable surplus, e.g., if M changes from 1 to 2, the expected increase in productivity is about 50 per cent.

The assumption of a constant M during the entire life of a clupeoid is very questionable; there is considerable evidence that M increases with age.

Determination of the correct M value is critically dependent on accurate ageing. Unfortunately ageing of clupeoids is difficult and the California anchovy is no exception. Expert investigators agree the Peruvian anchoveta lay down two ring marks per year and consequently interpretation of all scales is based on a six-month marking interval. For the northern anchovy no such consensus exists; there is extensive evidence that false annuli are common, yet it appears that in most years the older fish lay down only one annulus. It may well be that the two rings are laid down during the first year of life as has been found for the California sardine. The possibility of substantial error in the age data for the northern anchovy is clearly in the direction of counting false annuli. This bias, if significant, means the population has a younger age structure than commonly thought and that the true natural mortality rate is higher than that estimated from interpreting the time interval as one year between the occurrence of ring marks.

Density Dependent Processes

Existence of various compensatory mortality mechanisms is the primary reason fish populations can exist under the pressure of heavy exploitation. Replacement species such as the anchovy are particularly hardy with high prolificacy and broad niche requirements. The report of the Second Session of the Panel of Experts on the Population Dynamics of Peruvian anchoveta (1971) discusses the high productivity of anchoveta at stock sizes well below one-half the size of the virgin stock where the commonly used logistic curve has a point of maximum productivity. For the Peruvian anchoveta surplus productivity appears to decrease almost linearly as stock size increases. Although no observations are available at extremely low stock sizes, the highest productivities observed so far have occurred at stock sizes well to the left of one-half the virgin stock size. The fish production system of the Peru Current is functionally comparable to a chemostat (a continuous culture device for rearing populations of organisms such as bacteria or phytoplankton) and the same types of growth kinetic analysis applied to chemostat data can be used to analyze the Peruvian anchoveta data. This type of analysis cannot be applied to the California system where there is no exploitation history.

The panel of experts on the Peruvian anchoveta commented,

> "Aspects of the anchovy life history that suggest the model (hyperbolic or Michaelis-Mention equation) is realistic are that recruitment appears to have a maximum at rather less than half the virgin stock, as evidenced by the strong year-class that recruited at the beginning of 1970. The spawning pattern, together with the known proclivity of the anchovy to consume its own eggs, suggests a high degree of density dependent feed back. For example, a very successful August-September spawning can greatly dampen the February spawning, and vice versa. Conversely, a poor August-September spawning would be followed by a successful February spawning provided there are enough adults.
>
> As the stock decreases its potential productivity can be expected to increase until the population suddenly collapses. Observations on the behaviour of actual fish stocks at low stock levels show that productivity is apt to be extremely erratic as well as extremely high. Examples of populations with high production at a time of severe stress caused by over-fishing or other causes just before they collapsed include the California sardine, and several of the stocks in the Great Lakes. In these circumstances it is of utmost importance to set up an accurate and timely monitoring system to detect any evidence of population distress such as recruitment failure. This must then be used to reduce fishing quickly to a value that will allow the population to recover to a level that will ensure its survival as the dominant species in the Peru Current system."

It is reasonable to expect the same mechanisms operating in the Peruvian Current to control the productivity of the California anchovy stocks. Observations of northern anchovy in aquaria at the National Marine Fisheries Service

Laboratory at La Jolla, California, have shown that individual female anchovy are capable of extended continuous spawning if provided with sufficient food. It is well known that clupeoids are capable of reabsorbing eggs, even though the factors that trigger reabsorbtion are not well understood. Ability to control the fecundity or production of eggs per female is a powerful population stabilizing force. For example, a food shortage resulting from overfeeding by an extremely large population[1] would generate an automatic reduction in production of eggs and subsequently in the numbers of new recruits. Conversely, a small population and abundant food would stimulate higher egg production. Egg production that is directly proportional to food consumption is commonly found in zooplankton; the population consequences of this type of mechanism would be quite different for anchovies however, because of time lags and nonlinearities in response. Peruvian anchoveta populations have two spawning peaks, the magnitudes of which are inversely related. During the past decade or so since observations have been made, the overall production of recruits is remarkably constant from year to year. Such constancy implies a successful first spawning and/or the resulting high abundance of young anchovy fry somehow act to depress production of recruits from the second spawning peak; if the first spawning is unsuccessful, the second spawning peak will tend to be larger.

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[1] Approximately 30% of the water in the California current system is filtered daily during certain seasons according to Dr. P. Smith, Director of the Population Dynamics Section of the NMFS La Jolla Laboratory.

The indiscriminate filter feeing habits of spawning adults operate as another compensatory devise by severely reducing survival of eggs in large spawning concentrations. The same ultimate effect is produced by factors that cause growth to vary inversely with population density. Growth depression causes production of fewer eggs at a given age. There are preliminary indications for the Peru stocks that L_∞, a measure of ultimate size obtained by an individual under given environmental conditions, may fluctuate with population density.

All these factors act to stabilize population biomass. However, it is almost impossible to forecast exactly the manner and degree of effect that will result from the action of any particular combination of density dependent operators. Several dependent factors included in the simulation model are described below; the reader should keep in mind that extrapolations to population sizes either larger or smaller than those actually observed in the California Current system are at best only informed extrapolations.

General Description of Anchovy Model

A model of the biological behavior of Peruvian anchoveta, *Engraulis ringens*, developed by G. J. Paulik and staff members of the Center for Quantitative Science, was used as the basis for modeling the behavior of northern anchovy, *Engraulis mordax*. This model performs population accounting (reproduction and recruitment, ageing, growth, natural mortality, and harvesting) for the exploited stock. Most of the population's parameters are read in as data before simulation begins and remain constant throughout the course of experiments. The exceptions to this rule are the variables which describe harvesting effort and capacity of the harvesting units; these variables are determined at monthly intervals during the course of the simulation.

Within each month, the order of operations is as follows: The harvesting and capacity variables for the fleet of 20 large sized vessels are passed to the anchovy model:

EFFD(H,S) = fishing effort (number of boats)
FPWD(H,S) = fishing power
HCAPAC(H,S) = capacity (MT/boat/day)
HDELT(H,S) = fraction of a month fished.

These variables are used to calculate equivalent standard effort, F(H,S), in terms of boats fishing the entire month instead of a fraction of it, and the total harvesting capacity per harvesting interval, CAPAC(H,S).

Next, the age structure is updated. Fish in each age group have some probability of transferring to the next age group in each month, MARK(S,M). These transition fractions are applied to each age group. Recruits due to enter in the current month are added to the first age group, and fish leaving the last age group disappear. Within each age group, the size of individual fish is computed as a weighted average of the sizes of newly entered and residual fish. From these adjusted sizes and numbers at age, the biomass of the population is then computed, BMASS(S,L).

Contribution to spawning is then calculated for the current month. The number of females eligible to spawn is determined by the proportion of females in the population, FRFEM(S), and by a maturity at age schedule, FRMATF(S,A). Of these mature females, the fraction which actually spawns during the month is given by FRSPAWN (S,M). Their egg production is computed by a fecundity at age schedule, EFEM(S,A). The results of this procedure are additions to the number of eggs deposited on the stock's spawning ground, EGG(G).

Instantaneous total mortality rates are then computed for each age group in the stock. Each age group may be subjected to a different total mortality, depending on natural mortality rate, NMORT(S,A), catchability coefficient, QCATCH(S,A), and availability factor, AVFR(S,L,M). For our purposes it has been assumed that natural mortality is constant, that catchability is age specific, and that availability fluctuates monthly. Letting FF denote total units of standard effort operating in the stock's location during the month, instantaneous total mortality rates are calculated for each age group as

$$Z(A) = QCATCH(S,A)*AVFR(S,L,M)*FF + NMORT(S,A).$$

Given these mortality rates, the catch of anchovy by the 20 large vessels may then be computed subject to the constraint that the total catch may not exceed total capacity of this harvester during the interval. At first, the harvester and natural mortality compete exponentially to determine the number of fish each would take if harvester capacity were unlimited. The harvester's catch in weight is computed as the product of the number of fish taken and their weight at the beginning of the harvesting interval. If this catch exceeds the interval capacity, the excess fish are placed in a special category, the harvester's fishing time is reduced in proportion to its excess catch, and it is made inactive for the remainder of the fishing interval. Fish credited to the harvester in excess of capacity are then subjected to natural mortality. Once the catch cycle has been performed, the number of fish remaining, CENSUS(S,A,L), is determined from the numbers caught and the numbers taken by natural mortality.

Growth in length which has occurred during the interval is then computed by a Von Bertalanffy equation. It has been assumed that growth is not density dependent. New individual weights at age are then computed by a cubic weight-length relationship.

Finally, future recruitment is calculated from the number of eggs deposited on the stock's spawning ground and the egg to recruitment survival rate. Recruitment is assumed to be density dependent and the model, therefore, adjusts egg survival in a compensatory manner according to user-supplied survival multipliers. The proper multiplier to be applied during the month is determined by the ratio of present biomass, BMASS(S,L), to the average or equilibrium biomass, WINF(S,L). This procedure determines the number of new recruits, RECRT(S,G,M), which will be available to the population after a delay of a number of months specified by RECINT(S,G,M).

Determination of Parameters

1. Composition and Natural Mortality

Miller (1955) determined that because of a winter check in growth a single annulus was laid down each year on northern anchovy scales; Collins and Spratt (1969) found a similar phenomenon for otoliths. Hence these two structures have been used to age anchovies and have yielded similar results: the oldest known anchovy had 7 annuli, but 5's and 6's are now quite rare. According to Baxter (1967), the oldest fish in Central California are usually 6's while in Southern California, they are 5's. Hence the model was set up to handle 7 age groups: ages 0-6. This assumes that ages 0-4 are the most numerous groups, that ages 5-6 are rare, and that, upon turning 7, an anchovy dies of old age, and leaves the system.

Estimates of the fraction of the population which is female have been obtained from the sources listed in Table 1. These yielded an overall average for the central anchovy stock of 56%.

Biomass of the central spawning population was determined by Ahlstrom (1968) to be 4.5-5.6 million tons during the period 1962-65. Messersmith, Baxter and Roedel (1969) report 4-5 million tons as their consensus for the period 1962-66. Kramer and Smith (1971) state that biomass has been fluctuating between 5-8 million tons since 1962. Hence, for the model, average or equilibrium biomass of the spawning population was set at 5 million tons (4.55 million MT).

Before determining the initial numbers at age, we first obtained an estimate of natural mortality. Schaefer (1967) reports that his analysis of age frequency catch curves for northern anchovy yielded an estimate of $Z = 1.10$. Since the fishery was so light for the years analyzed, he considers this to be a reasonable approximation to M and to be quite comparable to his estimates of M for Peruvian anchoveta: (1.0-1.2). This is also quite comparable to Gulland's (1968) estimate of M for anchoveta: (1.0-1.3).

Assuming that the biomass of adults in the central population is in equilibrium (4.55×10^6 MT) and that fishing mortality is negligible, the initial numbers at age may be obtained from weights at age, survival rate, and biomass estimates. At month 1, total biomass of the adults, i.e. ages 1-6, is the sum of the biomasses of each age group:

$$BMASS = \sum_{i=1}^{6} w_i N_i \quad .$$

If the population is in equilibrium, then N_i may be expressed as

$$N_i = N_1 s^{i-1} \qquad (1)$$

where N_1 is the number of age 1's. Biomass of the adults may then be expressed as

$$BMASS = N_1 \sum_{i=1}^{6} w_i s^{i-1}$$

or N_1 may be estimated as

$$N_1 = BMASS / \sum_{i=1}^{6} w_i s^{i-1} \quad .$$

Utilizing the initial weights from the growth section of this paper (Table 14), and given $s = 0.3329$ and $BMASS = 4.55 \times 10^6$ MT, then

$$\hat{N}_1 = 228.85 \times 10^9 \quad .$$

All other numbers at age may be determined by (1), yielding the results of Table 2. Note that initially no age 0's are in the population since, according to the section on marking fractions, all 0's become 1's by the end of month 12; thus the only 0's present should be those just entering as new recruits in month 1.

2. Spawning

To determine the fraction of this population which spawns each month, Ahlstrom's (1966) annual larval counts for the years 1951-59 were converted into fractional occurrences by month; then an average monthly value was determined. Since eggs require only 2-4 days to hatch (Frey, *ibid.*), it has been assumed that these average monthly fractional occurrences of larvae are measures of the incidence of spawning during their respective months. Further credence is given to this assumption by Ahlstrom's (1965) data which indicate that, during 1954-58, 57.4% of these monthly samples were composed of length group .250-.575 cm., the recently hatched group. Frey (*ibid.*) and Baxter (*ibid.*) indicate that females generally spawn twice a year. To force the model population to spawn twice, the indices of spawning activity were thus appropriately adjusted. The results are indicated in Table 3; note that spawning occurs throughout the year, and that, as stated by Miller (1956), spawning during the winter and spring contributes most to the annual recruitment of young fish.

A maturity at age schedule was derived from Figure 7 (spawning length schedule) and Table 6 (length at age) of Clark and Phillips (1952). Their spawning length data were not used directly because of large differences between the lengths at age of their samples and of those used for our growth calculations. These differences are probably caused by different sampling locations and times. The converted age-based data were felt to be comparable, however. The results are indicated in Table 4. It has been assumed that males and females mature according to the same schedule.

According to MacGregor (1968), female anchovies yield 574 eggs per gram of body weight per spawning. Hence if body weight is known, the fecundity of an individual may be determined from

$$E = 574w \; . \qquad (2)$$

The average weights of each age group were calculated from relationships in our growth section for March, the midpoint of the anchovy's major spawning period. These weights were utilized in equation (2) to determine the average fecundity at age. The results, given in Table 5, agree quite favorably with Baxter's (ibid.) statement that large females spawn 10-15 thousand eggs per batch or 20-30 thousand per year, given two spawnings per year.

3. Recruitment

Figure 3 from Clark and Phillips (ibid.) indicates that young fish of lengths 5-9 cm. began appearing in the bait catch during June-August in the central population; they considered these to be fish of the year. Miller (1955) noted the absence of the smallest sizes of the zero age group from commercial and bait catch samples; this absence is especially significant in the bait fishery which is prosecuted closer inshore than is the reduction fishery in areas where there is greater likelihood of encountering the smallest young of the year. He interpreted this absence as being due to behavior of the fish rather than a matter of gear selection: when 0-age fish become large enough and thus fast enough to move with the schools of adults, they change behavior and enter the fishable population. Miller concluded that this change in behavior occurred at approximately 8.5-9.0 cm.

Further evidence concerning the timing of the entry of new recruitment comes from the data of Miller and Wolf (1958) given in Table 6. These time series of mean lengths indicate that significant numbers of small fish apparently entered during the summer months, forcing the population mean to fall 2-3 cm. From all these data, the time of 1st entry of recruitment from the major spawning period was determined to be July. Fish spawned in January, the first month of the major spawning period, must be 6 months old if they enter in July; hence age at entry was set at 6 months. Furthermore, we determined from our growth calculations that size at entry was 8.9 cm. These results are comparable to those for Peruvian anchoveta, which apparently enter the fishable population at ages of 5-9 months and lengths of 8-11 cm. (Boerema *et al.*, 1967; Schaefer, *ibid.*).

To determine initial recruitment, we first calculated the replacement biomass, i.e. that weight which the population loses because of natural mortality in the equilibrium state. Recalling BMASS $= 4.55 \times 10^6$ MT and $s = 0.3329$,

$$BR = (4.55 \times 10^{12})(1-.3329) = 3.04 \times 10^{12}\text{gm}.$$

After calculating weight at entry of the age 0's as 7.3 gm., we may then determine their numbers as follows:

$$R = 3.04 \times 10^{12}/7.3 = 416.43 \times 10^{9}.$$

If we then assume that the size of a cohort of recruits entering in a given month is proportional to the incidence of spawning activity 6 months previous, we may apportion R over the year according to Table 7. Note that we need enter only the first 6 months of initial recruitment since the model takes over from month 7 onwards: recruits produced in month 1 enter 6 months later in month 7.

We have assumed that recruitment is density dependent, but specific data were lacking to formulate an anchovy stock-recruit relationship. However, we did obtain an estimate of egg to recruit survival for the equilibrium situation and then formulated hypothetical survival multipliers which indicated how such survival might vary as biomass or size of the population changed.

The equilibrium biomass (4.55×10^6 MT) may be apportioned to its constituent age groups (ages 1-6) by means of the following proportions:

$$p_i = w_i s_i / \sum_{i=1}^{6} w_i s_i$$

The replacement biomass (3.04×10^6 MT) gives the equilibrium biomass of age group 0. The maturity at age schedule may then be applied to these biomasses to determine the portion of each which is mature and hence spawning. Applying the fraction of the population which is female to the sum of these mature biomasses then yields the total biomass of mature females: 1.753×10^{12} gm. Then assuming 2 spawnings per year and recalling that 574 eggs are spawned per gm. of mature female biomass, we estimated the equilibrium number of eggs spawned annually as

$$EGGS = (1.753 \times 10^{12})(574)(2) = 2012.44 \times 10^{12} .$$

Recalling equilibrium recruitment numbers, we then obtained egg-recruit survival as

$$s_{ER} = 416.43 \times 10^9 / 2012.44 \times 10^{12} = 0.00021 .$$

Preliminary experiments conducted with the model indicated that this estimate was too low, and we subsequently raised egg-recruit survival to 0.00030, a highly satisfactory value which yielded a stable virgin population whose biomass averaged 4.9×10^6 MT.

As for the Peruvian anchoveta (see introductory comments), we have assumed that the northern anchovy stock-recruit relationship behaves according to the Beverton and Holt model:

$$R = S/(a + bS)$$

where R and S are the biomasses of recruits and spawners, respectively. As S becomes large, R may be shown to approach the limiting value

$$R_{max} = 1/b,$$

and so we may express b as a function of R_{max}:

$$b = 1/R_{max} .$$

R_{max} in turn may be expressed as some multiple of replacement biomass (3.04×10^6 MT), and b may then be expressed as

$$b = 1/(M)(3.04 \times 10^6) \ .$$

We may formulate an expression for egg-recruit survival based on the above Beverton and Holt model:

$$s(S) = 1/(a + bS) \ .$$

This in turn may be expressed as some constant and a variable multiplier which is a function of S:

$$s(S) = s_{ER}*SMULT(S) = s_{ER}*(1/(a+bS)) \ .$$

Expressing the multiplier as a function of the ratio between present biomass and average or equilibrium biomass yields

$$SMULT(S) = 1/(a + b\bar{S}\ RATIO)$$

where RATIO = $S/\bar{S}$.

Since $\bar{S}$ is a constant (4.55×10^6 MT), we may formulate a new b yielding

$$SMULT(S) = 1/(a + b'RATIO) \ .$$

At equilibrium, RATIO = 1, and letting SMULT = 1, we may determine a as a function of b':

$$a = 1 - b' \ .$$

Hence, we may find both a and b' given an arbitrary choice of M, the value by which replacement biomass is multiplied. These then may be used to generate multipliers, SMULT, for given RATIO values. This procedure gave rise to the 3 sets of multipliers indicated in Table 8. The model interpolates linearly between given multipliers as indicated in Figure 3; note that the curves defined are modified hyperbolas.

4. Fishing Mortality

Fishing mortality is apparently affected by seasonal availability factors. According to Paulaha (1970), school size is much larger in the spring-summer months than in the fall-winter ones. Baxter (*ibid.*) states that northern anchovies move inshore in the spring and then offshore in the fall and winter. And Miller's (1956) data suggest that an increase of adults occurs in the spring, that their abundance peaks in June-August, and that a decrease then occurs in the fall-winter months.

Examination of Messersmith's (*ibid.*) monthly catch per unit of effort data gave a more quantitative idea of how availability fluctuated. His monthly CPU's are plotted in Figure 4; for unknown data points, we assumed that their values could be obtained by linear interpolation between known values on either side. The trends of Figure 4 indicated that improved or improving availability was to be expected during the summer. We then found the average CPU for each month and normalized these values by dividing each by the largest monthly average. This yielded a measure of fractional availability whose monthly pattern is indicated in Figure 5.

The coefficient of catchability for northern anchovy was determined from Messersmith's (*ibid.*) CPUE data for purse seiners operating in Southern California during 1965-67. For these 2 seasons, 110 ton capacity purse seiners averaged 7.69 tons/hour. This figure was converted to catch per month in MT, assuming an

8 hour fishing day and that the vessels fished every day of the month:

$$\text{CPUE} = (7.69)(8)(30.6)(.91) = 1713.6\text{MT/vessel-month} .$$

Recalling Frey's (ibid.) comment that processors were able to handle only 1/2 the capacity of the present fleet, it was assumed that vessels were fishing at 50% efficiency. Utilizing this fact, the above CPUE was then used to estimate the coefficient of catchability that would be expected under conditions of maximum availability and maximum fishing time:

$$\text{QCATCH} = \text{CPUE}/(\text{AVFR*EFFIC*BMASS})$$

$$\text{QCATCH} = 1713.6/(1)(.5)(4.55 \times 10^6)$$

$$= 7.53 \times 10^{-4}.$$

On a yearly basis this rate then became

$$\text{QCATCH} = (12)(7.53 \times 10^{-4}) = 9.04 \times 10^{-3}.$$

Collins' (1969) age frequency distribution data for the period 1965-1967 indicated that 2's apparently were fully recruited into the fishery but that 0's and 1's were not. Consequently the coefficients of catchability affecting these latter 2 age groups was adjusted to account for their lack of availability to the fishery. Adjustment factors were obtained by comparing observed and expected catch in numbers of these 2 age groups. The expected catches were obtained by backcalculating from Collins' catch of 2's using our estimated natural mortality rate, i.e. s = 0.3329:

$$C\hat{N}_1 = CN_2/s$$

$$C\hat{N}_0 = C\hat{N}_1/s .$$

This procedure assumes that the same natural mortality rate applies to recruited and non-recruited 0's and 1's and that the biological effect of fishing is negligible. The results of this procedure are given in Table 9. The coefficients of catchability affecting these two age groups were then determined using the average availability factors as follows:

$$QCATCH_0 = (0.015)(9.04 \times 10^{-3}) = 0.14 \times 10^{-3}$$

$$QCATCH_1 = (0.151)(9.04 \times 10^{-3}) = 1.37 \times 10^{-3} .$$

Vessel efficiencies were determined from the data of Schaefer (ibid.) which indicate how efficiency varies with the capacity of purse seiners in the Peruvian anchoveta fishery (Table 10). These data were fitted by simple linear regressions and yielded the two line representation of Figure 6. We wished to determine the efficiencies of the following vessel sizes for which we also had economic performance figures: 60, 100 (our standard vessel), 140, 191, and 240 MT. The efficiency associated with each capacity was determined from the appropriate linear relationship and then normalized using the efficiency of the 110 ton (100MT) vessel as standard; the results are indicated in Table 11. We have also indicated the performance of these vessels when operating on jack mackerel.

5. Growth

According to Miller (1955), all anchovies have formed their scale annulus by mid April. We have interpreted this statement to mean that 100% of the population has formed a new annulus, i.e., had a birthday by May 1st. Given this fact, we formulated marking fractions, or proportions of the population having a birthday each month, from his bi-monthly cumulative distribution:

Dec-Jan .35 have formed an annulus
Feb-March .85 have formed an annulus
Apr-May 1.00 have formed an annulus

Assuming that numbers having birthdays are uniformly distributed in each two month period, we obtained the marking pattern for scales of Table 12.

Collins and Spratt (1969), however, have established June 1st as the date by which all fish have completed an otolith annulus. Since recent northern anchovy growth studies have utilized otoliths for ageing purposes, we decided to adjust the timing of the scale marking pattern to coincide with the otolith birthdate. Hence we have assumed that otoliths mark or age in the same pattern as scales but that they are delayed by one month due to the slower response of their harder structure. We thus have established June as the model's first or initial month.

The data of Collins (1969) have been combined over seasons and areas to yield the mean standard lengths and weights at age of Table 13. The first age 0 length was taken from Miller's (1955) data concerning age and size at recruitment. All the succeeding data points take their ages from the facts that Collin's samples were taken over a 7-month period, Oct-April; that January is the midpoint of that period; that the average age of the 0's is 10 months in January; and that the average age of all other age groups is found by adding successive increments of 12 months to the average age of the 0's.

As for Peruvian anchoveta (Boerema et al., ibid.) it has been assumed that growth in length is asymptotic and that the Von Bertalanffy growth equation adequately represents such growth:

$$L_t = L_\infty(1 - e^{-K(t-t_0)}) .$$

The parameters for this equation were determined by fitting the curve directly to the mean lengths of Table 13. The "Weighted Non-Linear Least Squares Estimation" computer program developed by Paulik and Gales (unpublished ms.) was used to carry out the fitting procedure and yielded the following estimates:

$$L_\infty = 15.91 \text{ cm.}$$

$$K = 0.32$$

$$t_0 = -2.08$$

As may be seen in Figure 7, the above growth curve fits the observed data rather well.

Again following the Peruvian anchoveta, a cubic relationship between weight and length was assumed for the northern anchovy:

$$W_t = qL_t^{\ 3}$$

Fitting the length and weight data of Table 13 to the linearized form of the above equation yielded the following estimate of q:

$$q = 0.01016 .$$

The initial lengths and weights calculated from these relationships and used to begin the simulation are given in Table 14. It has been assumed that growth is not density dependent.

Model Behavior

Experiments were first conducted to examine the behavior of the unexploited model population under different stock-recruit relationships. All 3 curves yielded similar results: after initial small adjustments, the population stabilized in 10 years time at average biomasses of 4.9 x 10^6 MT for curve 1, 4.8 x 10^6 MT for curve 2, and 5.1 x 10^6 MT for curve 3. During a given year, biomass typically was found to fluctuate within the range 4.3-5.4 x 10^6 MT for all 3 curves. In general, biomass would be at the lower end of its range at the beginning of a year, would rise to its upper value as the particularly large cohorts of recruits produced in the preceding winter and spring entered at mid-year, and then would drop as natural mortality took its toll in the face of lessened recruitment at the end of the year.

Differences between the 3 stock-recruit curves became apparent only after conducting experiments in which initial population sizes were first halved and then doubled. Figure 8 indicates the temporal behavior of biomass after halving the initial population and Figure 9 that after doubling it. Once again the model populations were in an unexploited state. In Figure 8, curve 1 essentially causes the population to recover its equilibrium value within the 1st year; curve 2 causes the population to over-react, reaching biomass values much greater than the equilibrium level during the first 2 years; curve 3 causes the population to recover quite slowly, taking some 3-4 years to reach levels construed to be normal. In Figure 9, as expected for all 3 curves, the population takes much more time to recover equilibrium than when initialized at low population sizes. In the Beverton and Holt stock-recruit model, low sizes are much more critical than are high ones, and this theoretical tendency to correct low levels quickly and high ones slowly agrees with *a priori* observations of general anchovy dynamics. The major differences between the 3 stock-recruit curves then are in how they respectively behave at low population levels, and in this regard curve 1 appears to behave in the most satisfactory manner.

Further preliminary experiments were conducted to examine the behavior of the model population under the 3 stock-recruit curves when being exploited by a constant fishery. The fishery consisted of 100 vessels, averaging 240 MT capacity each and operating 18 days per month during a 12 month season. Table 15 indicates the average biomasses and annual catches observed for the 3 curves during the 10 years of simulated operation. After starting in year 1 upon a virgin population, both biomasses and catches quickly declined. The interesting feature of Table 15 is that biomass and catch did not decline steadily but actually increased in some years; this phenomenon is most pronounced in curve 2 which tended to produce larger catches and biomasses than did the other two curves. Such behavior occurs because of compensatory recruitment. Once heavy fishing pressure forces biomass down to a level defined as critical by a given stock-recruit curve the population reacts to correct the situation with a spurt of increased productivity, i.e. larger than usual recruitment. The degree of correction or biomass increase depends upon the configuration of the stock-recruit curve used. Hence curve 2 defines a population which is highly productive at low population levels while curves 1 and 3 define moderately productive ones. Curve 1 appears to give the most stable catch pattern and is slightly more productive than is curve 3.

The management implications of different stock-recruit relationships are made obvious by the above experiments. A highly productive population could support a much larger fishery or level of effort than could a moderately productive one. Hence, since the configuration of the curve pertaining to northern anchovies is unknown, management should be attempting to define this highly critical relationship; this is particularly true if fishing effort should grow to any substantial level in the future. For present purposes, however, we have used only curve 1 to define this population's compensatory stock-recruit processes since of the 3 curves this one behaved most satisfactorily in the preliminary experiments.

A final preliminary experiment was conducted to validate model behavior with respect to the current fishery situation. The anchovy fleet presently consists of 20 purse seiners, averaging

100 MT capacity each and operating 18 days per month during an 8 month season which begins in mid-September and ends in mid-May. During such a season the fleet will take 70-75 thousand MT while biomass averages 4.5 - 4.6 x 10^6 MT. Figure 10 indicates the temporal behavior of catch and anchovy biomass during the 10 years of simulated operation. As expected, biomass is not greatly affected by the presence of a fishery and approaches a limiting value of 4.5 x 10^6 MT. Catches similarly appear to level out, approaching a value of 75 thousand MT. Based upon these results, it was felt that the model was a valid representation of the biological behavior of northern anchovy and would yield creditable results in experiments involving other fishery configurations.

THE JACK MACKEREL BIOLOGICAL SECTOR

General Description of Jack Mackerel Model

Given the paucity of basic growth and mortality data for jack mackerel, *Trachurus symmetricus*, a simple constant biomass model was constructed as a first approximation of this species' biological behavior. The model assumes that, despite the losses in numbers imposed by man or nature, the population compensates in some manner to maintain biomass at a constant or equilibrium level. The mechanism through which the population reacts is not explicitly defined in the model but might be accounted for by compensatory effects in growth, recruitment, or survival. It is assumed that such effects occur instantaneously so that a time lag does not exist between incidences of mortality and the population's compensatory reaction. As a result, the population's biomass remains constant with time, even in the face of fishing pressure. This representation is consistent with MacGregor's (1966) statement that this population has been relatively stable compared with the other three pelagic species taken by the Wetfish Fishery: Pacific sardine, Pacific mackerel, northern anchovy.

Such a simple model is valid only as long as fishing mortality does not become so great that the population must undertake unreasonably large compensatory adjustments. Several facts indicate that fishing mortality has indeed remained within reasonable bounds. Fitch (1956), MacGregor (*ibid.*) and Blunt (1969) indicate that the fishery historically has operated only upon a small inshore portion of the species' overall North Pacific range; hence only a part of the total population is apparently vulnerable to fishing mortality. Catch statistics compiled by Frey (ibid.) indicate that fishing pressure on this vulnerable segment historically has been slight. The largest catch of 75,000 tons was taken in 1952; the average catch of 25,000 tons taken during the period 1966-69 is fairly representative of the current capabilities of the Wetfish Fleet with respect to this species. Taking Ahlstrom's (1968) conservative estimate of the biomass of jack mackerel in the California Current Region, 1.4 million tons, we see that currently the fleet is taking only 1.8 percent of the biomass annually and that even the largest catch was only some 5 percent of the biomass available. Hence it seems reasonable to assume that past and present fishing mortalities have had an insignificant effect upon the population. And since in our simulation experiments we did not use levels of effort giving catches which exceeded the 1952 maximum, this simple model seemed to be a valid representation of the jack mackerel's biological behavior.

Mathematical Formulation

If the biomass of stock S is constant, then catch in weight from that stock during month M may be expressed as

$$\mathrm{CATCH}(S,M) = A(M)*\mathrm{PEQ}(S) \qquad (1)$$

where PEQ(S) is biomass and A(M) is the monthly fishing mortality rate which may be defined further as

$$\text{A(M)} = \text{AVFR(S,M)*QCATCH(S)*FMØRT.} \qquad (2)$$

We define AVRF(S,M) as the availability coefficient of stock S in month M and QCATCH(S) as the catchability coefficient of stock S. FMØRT is the sum of adjusted effort expended by all harvesters operating on stock S in month M and is expressed as

$$\text{FMØRT} = \sum_{\text{H}} \text{EFFD(H,S)*FPWD(H,S)*HDELT(H,S)/30.6} \qquad (3)$$

where EFFD(H,S) = number of vessels used by harvester H on stock S in month M.

FPWD(H,S) = average fishing power of H's vessels.

HDELT(H,S) = number of days/month expended by H on stock S in month M.

The catch of stock S in a given year is then given by the sum of monthly catches:

$$\text{CCATCH(S)} = \sum_{\text{M}} \text{CATCH(S,M)} \qquad (4)$$

Determination of Parameters

Ahlstrom's (1968) conservative estimate of jack mackerel biomass converts into PEQ(S) = 1.28 million MT. Following Blunt's (*ibid.*) statement that an explicit seasonal pattern is not demonstrated by monthly landings of this species, we set a constant availability coefficient: AVFR(S,M) = 1. Personnel of the California Department of Fish and Game indicate that, on the average, a vessel will fish 18 days per month; hence to indicate a full month's fishing, HDELT(H,S) = 18. Each day represents one vessel trip.

Equation (4) may be rewritten as

$$\mathrm{CCATCH(S)} = \mathrm{PEQ(S)} \sum_{M} \mathrm{A(M)}.$$

We previously used this form to estimate the sum of monthly fishing mortality rates:

$$\sum_{M} \hat{\mathrm{A}}\mathrm{(M)} = \mathrm{CCATCH(S)/PEQ(S)} = 0.018$$

With this estimate and information on effort and relative fishing power, we may then estimate QCATCH(S) for jack mackerel and complete the data requirements of the model: Recalling (2) and given that QCATCH(S) is constant and that AVFR(S,M) = 1, we may write

$$\sum_{M} \mathrm{A(M)} = \mathrm{QCATCH(S)} \sum_{M} \mathrm{FM0RT}$$

which yields

$$\mathrm{QCA\hat{T}CH(S)} = 0.018/\sum_{M} \mathrm{FM0RT}. \qquad (5)$$

Recalling (3) and given that HDELT(H,S) = 18 for all harvesters, the sum of fishing mortality rates may be expressed as

$$\sum_{M} \mathrm{FM0RT} = (18/30.6)\sum_{M}\Big(\sum_{H} \mathrm{EFFD(H,S)*FPWD(H,S)} \Big). \qquad (6)$$

If FPWD(H,S) is considered fixed for each harvester, then (6) may be rearranged to give

$$\sum_{M} \mathrm{FM0RT} = (18/30.6)\sum_{H}\Big(\mathrm{FPWD(H,S)} * \sum_{M} \mathrm{EFFD(H,S)} \Big). \qquad (7)$$

Determining FPWD(H,S). There are essentially two groups of vessels involved in taking jack mackerel: 20 large vessels averaging 110 tons capacity each, 10 small ones of 45 tons each. The data of Mitani and Ida (1965) presented in Table 16 indicate that Japanese purse seiners of different capacities demonstrate markedly different fishing powers when fishing for jack mackerel (Trachurus japonicus). The relationships indicated in Figure 11 were obtained from the data of Table 16 by linear regression (a two-line representation gave the least variance). These were used to determine fishing powers for the two harvester groups operating on jack mackerel in the Wetfish system; these fishing powers were then standardized, yielding

FPWD(1,S) = 1.00 for small vessels

FPWD(2,S) = 1.66 for large vessels.

Determining Σ EFFD(H,S). Communication with the California Department of Fish and Game indicated that the 10 small vessels operate almost exclusively on jack mackerel during the year and that the 20 large vessels take this species only when the northern anchovy fishery is closed. The series of monthly catch statistics given by Heimann and Frey (1968) indicated further that during months of anchovy closure some vessels also operate on bluefin tuna and Pacific bonito. To reflect these facts, it was assumed that small vessels always fish on jack mackerel and that 1/4 of the 20 large vessels always move into the bluefin tuna and Pacific bonito fisheries during months of complete closure of the anchovy fishery, i.e. this fraction leaves the Wetfish system. During May and September, when the anchovy fishery is closed for only 1/2 month, all 20 large vessels were assumed to spend 1/2 of the month operating on anchovies and 1/2 on jack mackerel, i.e. in effect 10 large vessels fish on each species. These assumptions gave rise to the effort pattern outlined in Table 17, from which was obtained the total efforts of each harvester group:

$$\Sigma\ \text{FPWD}(1,S) = 120 \text{ small vessel-months}$$

$$\Sigma\ \text{FPWD}(2,S) = 80 \text{ large vessel-months.}$$

Equations (5) and (7) and the above estimates were then used to give the estimate (expressed on an annual, rather than monthly, basis):

$$\text{QCATCH}(S) = 1.21 \times 10^{-4}\ .$$

Table 1 - Estimates of the fraction of females in the total northern anchovy population.

Source	Estimate
Clark and Phillips (1952)	0.57
Miller, Daugherty, Felin, and MacGregor (1955)	0.56
Miller and Wolf (1958)	0.52
MacGregor (1968)	0.56
Collins (1969)	0.60

Table 2 - Initial numbers at age for the total northern anchovy population .

Age Group	Size*
0	0
1	228.85×10^9
2	76.18×10^9
3	25.36×10^9
4	8.44×10^9
5	2.81×10^9
6	0.94×10^9

*Note that at the beginning of month = 1 there are no residual age 0's since all have theoretically become 1's by the end of month 12. See section on growth. Initial recruitment input handles the incoming age 0's for month = 1.

Table 3 - Incidence of monthly spawning activity by northern anchovy as determined from larval counts.

Month	Fractional Occurrence	Adjusted Occurrence*
1 June	.10	.20
2 July	.05	.10
3 Aug.	.03	.06
4 Sept.	.01	.02
5 Oct.	.02	.04
6 Nov.	.03	.06
7 Dec.	.03	.06
8 Jan.	.11	.22
9 Feb.	.20	.40
10 March	.17	.34
11 April	.17	.34
12 May	.08	.16

*Adjusted to insure 2 spawnings per year.

Table 4 - Maturity at age schedule of northern anchovy.

Age Group	Fraction Mature
0	.10
1	.40
2	.80
3	.95
4	1.00
5	1.00
6	1.00

Table 5 - Fecundity at age of northern anchovies. Indicated figures are number of eggs per spawning.

Age Group	Average Weight*	Fecundity
0	9.1	5,200
1	14.9	8,600
2	20.4	11,700
3	25.1	14,400
4	28.9	16,600
5	31.9	18,300
6	34.2	19,600

*Average weight in grams in month 10, March, the midpoint of the major spawning period.

Table 6 - Time series of population means from northern anchovy catch samples.

Period of Sample	1954-55 Season Los Angeles Reduction Fishery	1956-57 Season San Diego Bait Fishery
A-M	-	11.4
J-J	9.6	8.2
A-S	9.0	10.1
O-N	9.5	11.0
D-J	-	-
F-M	12.0	-

Table 7 - Initial recruitment of northern anchovies based upon an annual equilibrium requirement of 416.43 x 10^9 age 0's.

Month Recruited	Month Produced	Incidence of Spawning	Size of Cohort x 10^9
1 June	7 Dec.	.03	12.49
2 July	8 Jan.	.11	45.81
3 Aug.	9 Feb.	.20	83.29
4 Sept.	10 March	.17	70.79
5 Oct.	11 April	.17	70.79
6 Nov.	12 May	.08	33.31
7 Dec.	1 June	.10	41.64
8 Jan.	2 July	.05	20.82
9 Feb.	3 Aug.	.03	12.49
10 March	4 Sept.	.01	4.16
11 April	5 Oct.	.02	8.33
12 May	6 Nov.	.03	12.49

Table 8 - Egg to recruit survival multipliers for northern anchovy. Each multiplier corresponds to a given ratio between present biomass and equilibrium on average biomass.

	Curve	1	2	3
	M	1.1	1.05	1.2
	a	-.3606	-.4254	-.2473
Ratio	b	1.3606	1.4254	1.2473
.33		11.3	22.2	6.1
.67		1.8	1.9	1.7
1.00		1.0	1.0	1.0
1.33		.69	.68	.71
1.67		.52	.51	.54
2.00		.42	.41	.44
2.33		.36	.35	.38
2.67		.31	.30	.32
3.00		.27	.26	.29
3.33		0	0	0

Table 9 - Availability adjustment factors of northern anchovy ages 0 and 1.

Season		Age 0	Age 1
1965-66	Observed	35.4	116.3
	Expected	3,457.8	1,151.1
	Availability	0.010	0.101
1966-67	Observed	73.6	245.6
	Expected	3,686.1	1,227.1
	Availability	0.020	0.200
	Average	0.015	0.151

Table 10 - Efficiencies of purse seiners fishing for Peruvian anchoveta (Schaefer, 1967).

Vessel Capacity (MT)	Efficiency
63.6	.531
74.1	.606
99.3	.784
120.6	1.000
141.0	1.051
167.7	1.174
211.3	1.477
267.7	1.557

Table 11 - Efficiencies of large sized vessels when operating upon northern anchovies and jack mackerel.

Capacity (MT)	Anchovy Efficiency: Calculated	Anchovy Efficiency: Normalized	Jack Mackerel*
60	0.536	0.681	1.37
100	0.787	1.000	1.66
140	1.038	1.319	1.67
191	1.358	1.726	1.68
240	1.518	1.929	1.69

*See jack mackerel discussion for procedure used to obtain these efficiencies.

Table 12 - Marking fractions by month for northern anchovies.

Scale Month	Otolith* Month	Proportion Marking	Cumulative Proportion
Dec.	Jan.	.17	.17
Jan.	Feb.	.18	.35
Feb.	March	.25	.60
March	April	.25	.85
April	May	.15	1.00

*Pattern used in this model.

Table 13 - Mean standard lengths and weights at age of northern anchovies obtained in catch samples.

Age Group	Age in Months	Length (cm.)	Weight (gm.)
0	6	8.5	-
0	10	10.2	10.7
1	22	11.7	16.2
2	34	12.3	18.9
3	46	13.4	24.5
4	58	14.2	29.1
5	70	14.7	32.3
6	82	15.1	35.1

Table 14 - Initial lengths and weights of northern anchovy used to begin the simulation in month 1.

Age Group	Length	Weight
0	7.9	5.1
1	10.1	10.6
2	11.7	16.3
3	12.9	21.6
4	13.7	26.1
5	14.3	29.7
6	14.7	32.6

Table 15 - Behavior of the northern anchovy population given 3 different stock-recruit relationships and a fishery consisting of 100 vessels averaging 240 MT capacity and a 12 month season.

		Ave. Biomass (10^6MT)			Catch (10^6MT)		
Year	Curve:	1	2	3	1	2	3
1		4.6	4.7	4.6	1.22	1.22	1.22
2		3.8	3.8	3.9	.85	.77	.85
3		3.3	3.3	3.3	.68	.68	.68
4		3.6	4.1	3.4	.65	.68	.62
5		3.7	4.4	3.3	.72	.86	.65
6		3.4	3.7	3.6	.67	.78	.64
7		3.4	3.6	3.6	.65	.68	.71
8		3.4	3.5	3.3	.65	.70	.66
9		3.3	3.9	3.3	.65	.69	.64
10		3.7	4.1	3.3	.65	.80	.64

Table 16 - Power factors associated with tonnages of Japanese purse seiners fishing for *Trachurus japonicus* (Mitani and Ida, 1965).

Tonnage of Vessel (MT)	Power Factor
15	.498
25	.826
40	1.000
75	1.758
150	1.764
350	1.821

Table 17 - Monthly composition of the effort expended on jack mackerel in terms of number of vessels and size category.

Month	Small Vessels	Large Vessels	Total
1 June	10	15	25
2 July	10	15	25
3 Aug.	10	15	25
4 Sept.	10	10	20
5 Oct.	10	-	10
6 Nov.	10	-	10
7 Dec.	10	-	10
8 Jan.	10	-	10
9 Feb.	10	15	25
10 March	10	-	10
11 April	10	-	10
12 May	10	10	20
Total	120	80	200

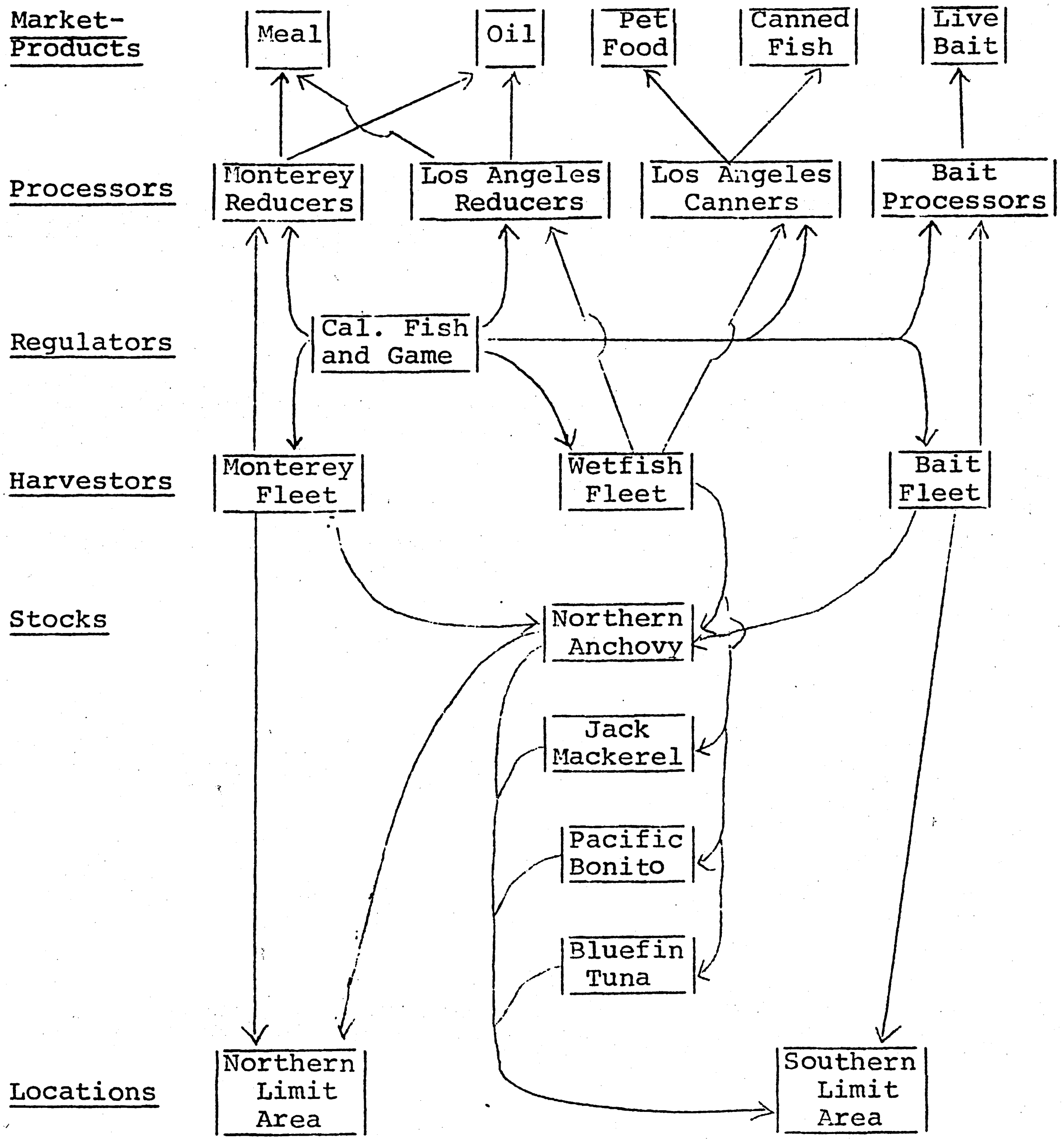


Figure 1 - Graphic representation of the logical relationships between sectors of the total northern anchovy fishery system.

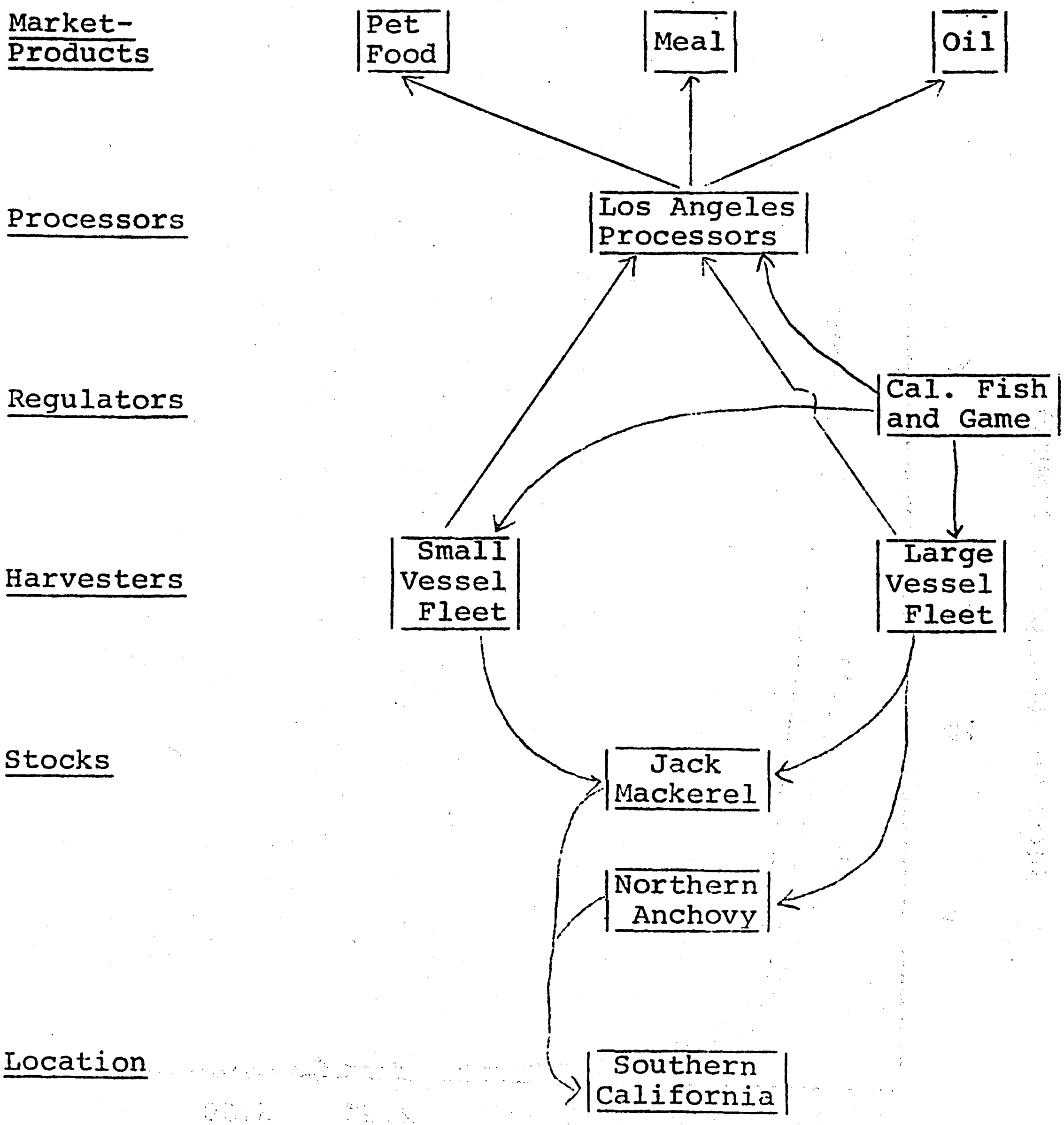


Figure 2 - Graphic representation of the logical relationships between sectors of the simplified northern anchovy system.

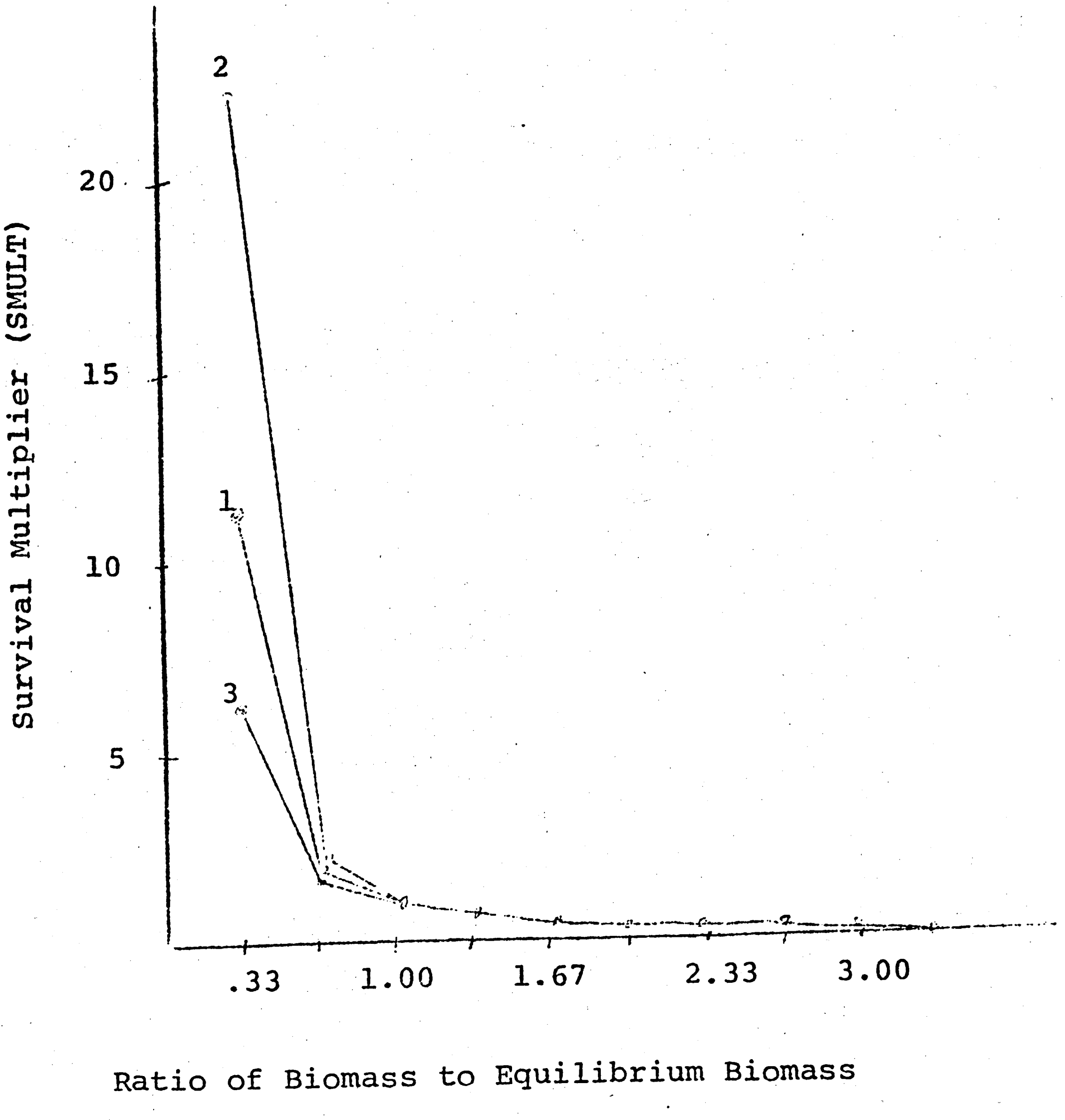


Figure 3 - Comparison of egg-recruit survival multipliers used to define stock-recruit relationships for northern anchovy.

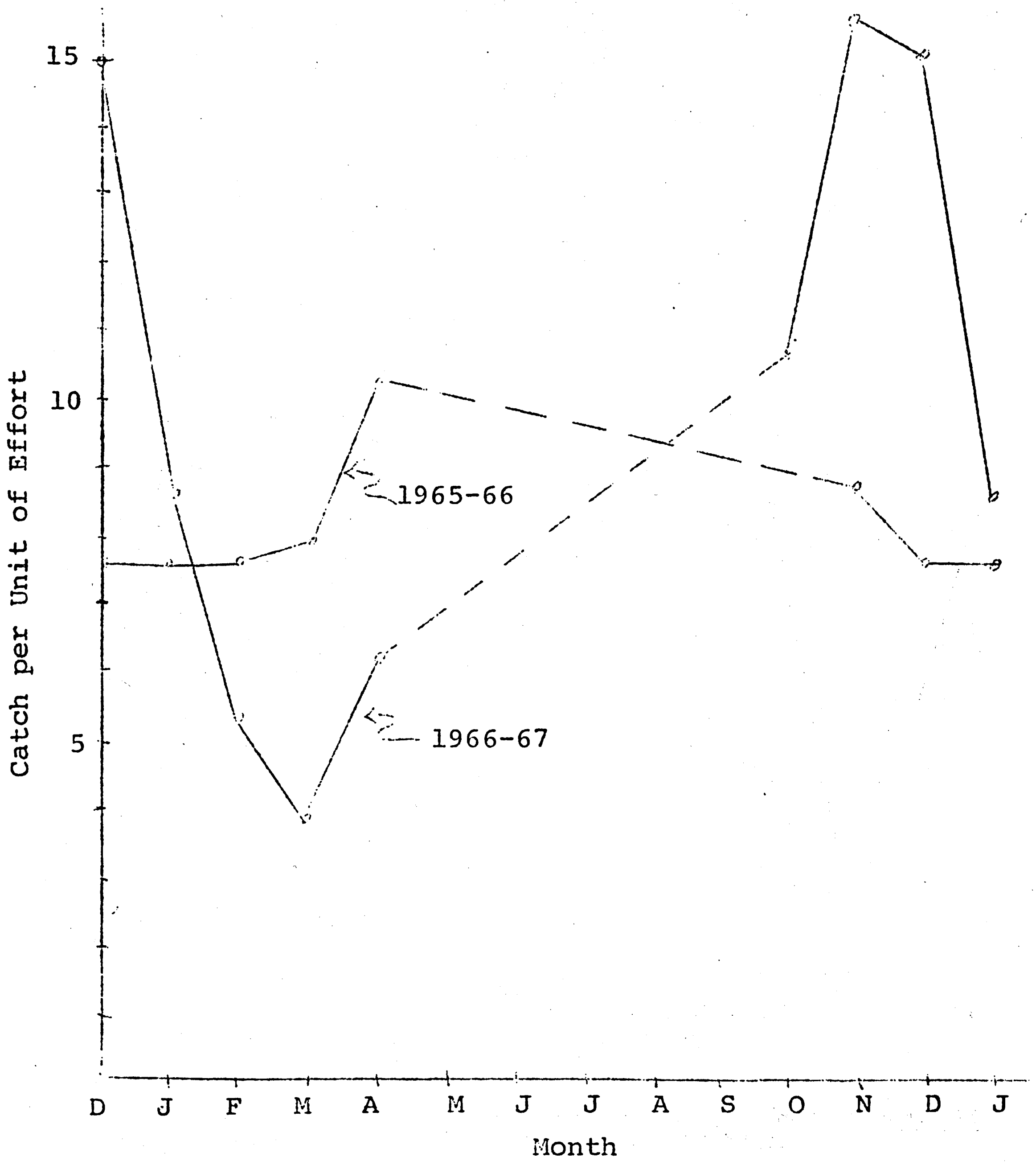


Figure 4 - Monthly cycle of catch per unit effort for northern anchovy. Dashed line indicates interpolated values, i.e. no fishing in these months (Messersmith, 1969).

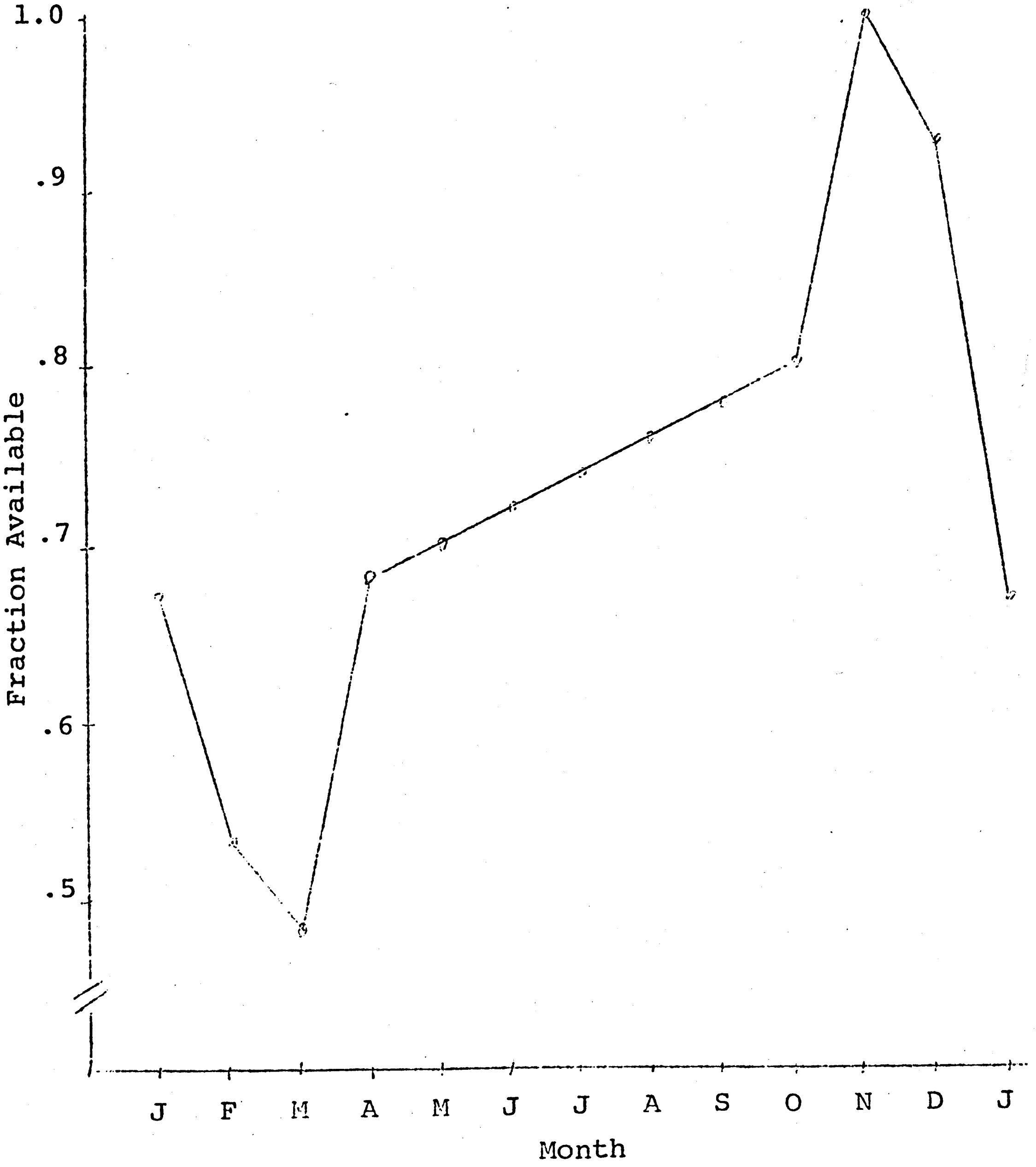


Figure 5 - Average fractional availability of northern anchovy in the Southern California area.

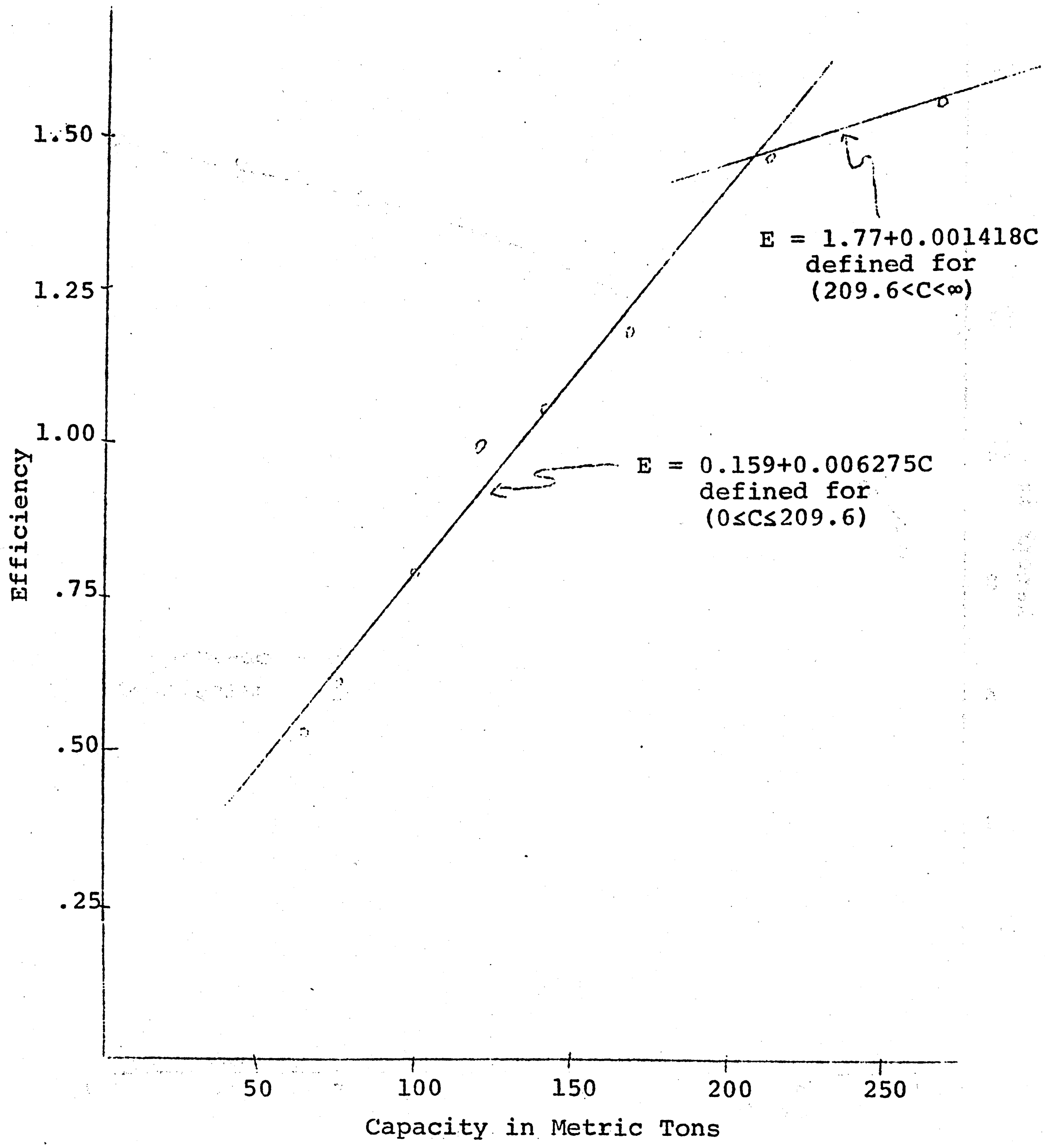


Figure 6 - Relation between efficiency and capacity of Peruvian purse seiners fishing for anchoveta (Schaefer, 1967).

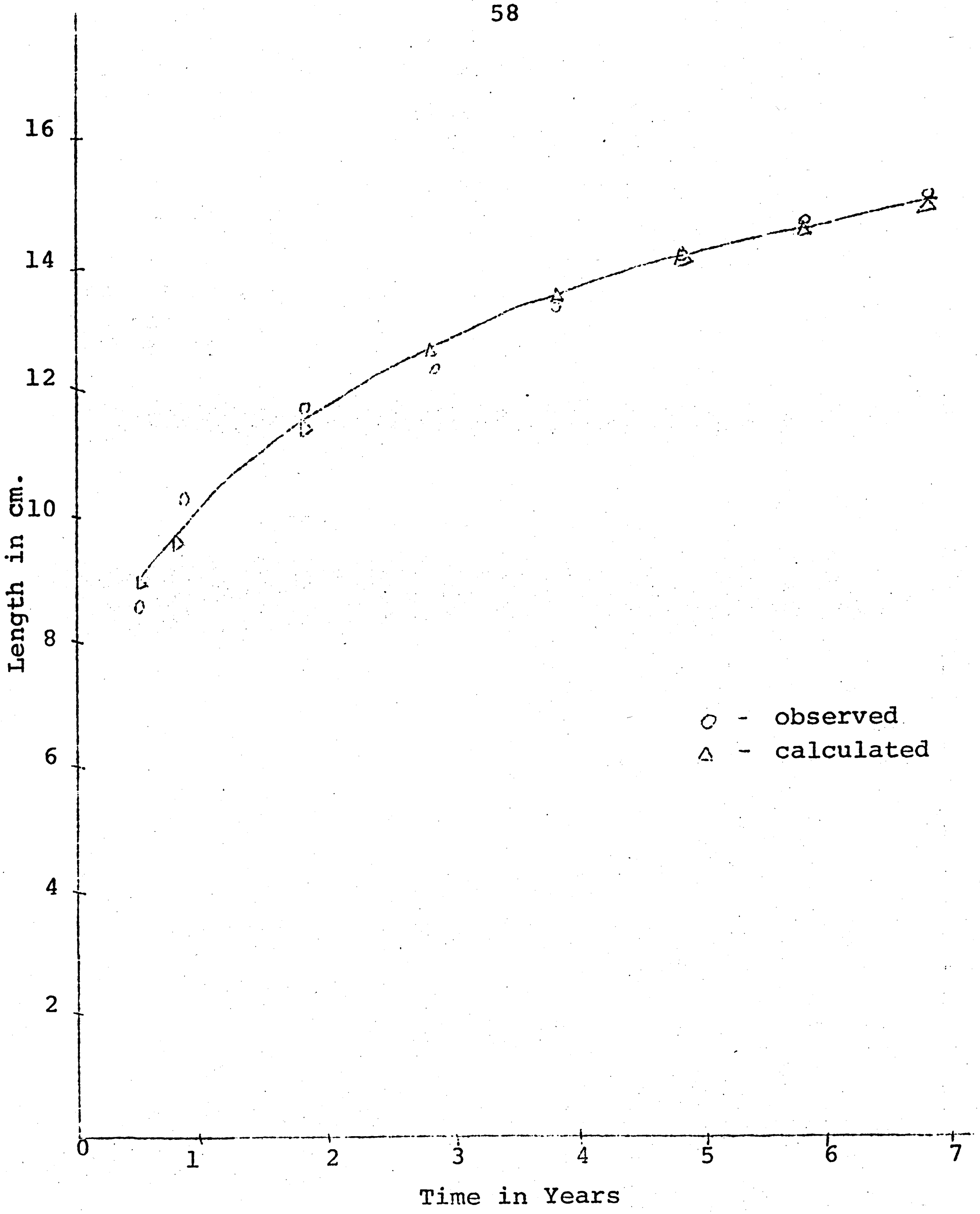


Figure 7 - Asymptotic growth in length of northern anchovies.

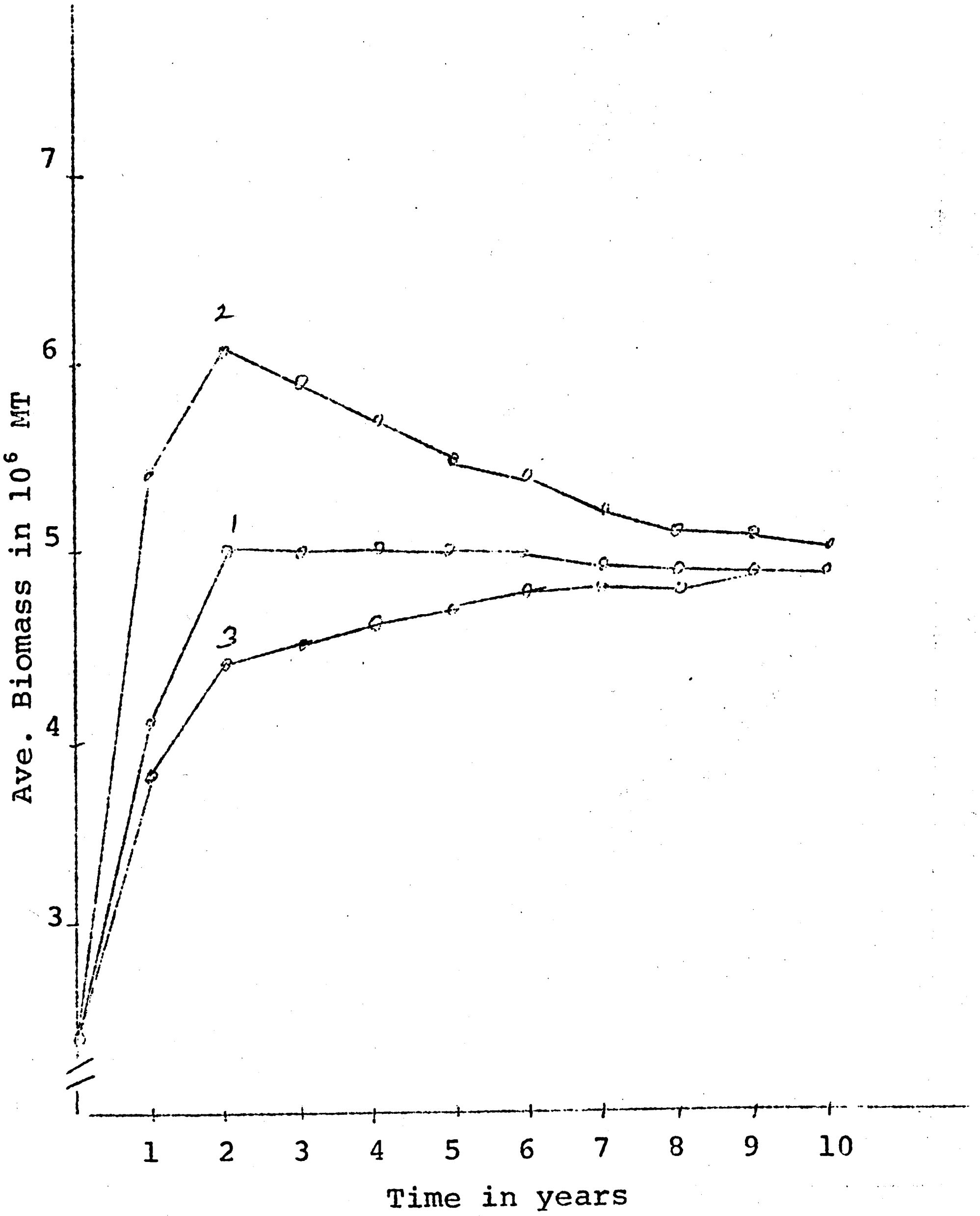


Figure 8 - Behavior of the unfished northern anchovy population given 3 different stock-recruit curves and an initial population size 1/2 normal.

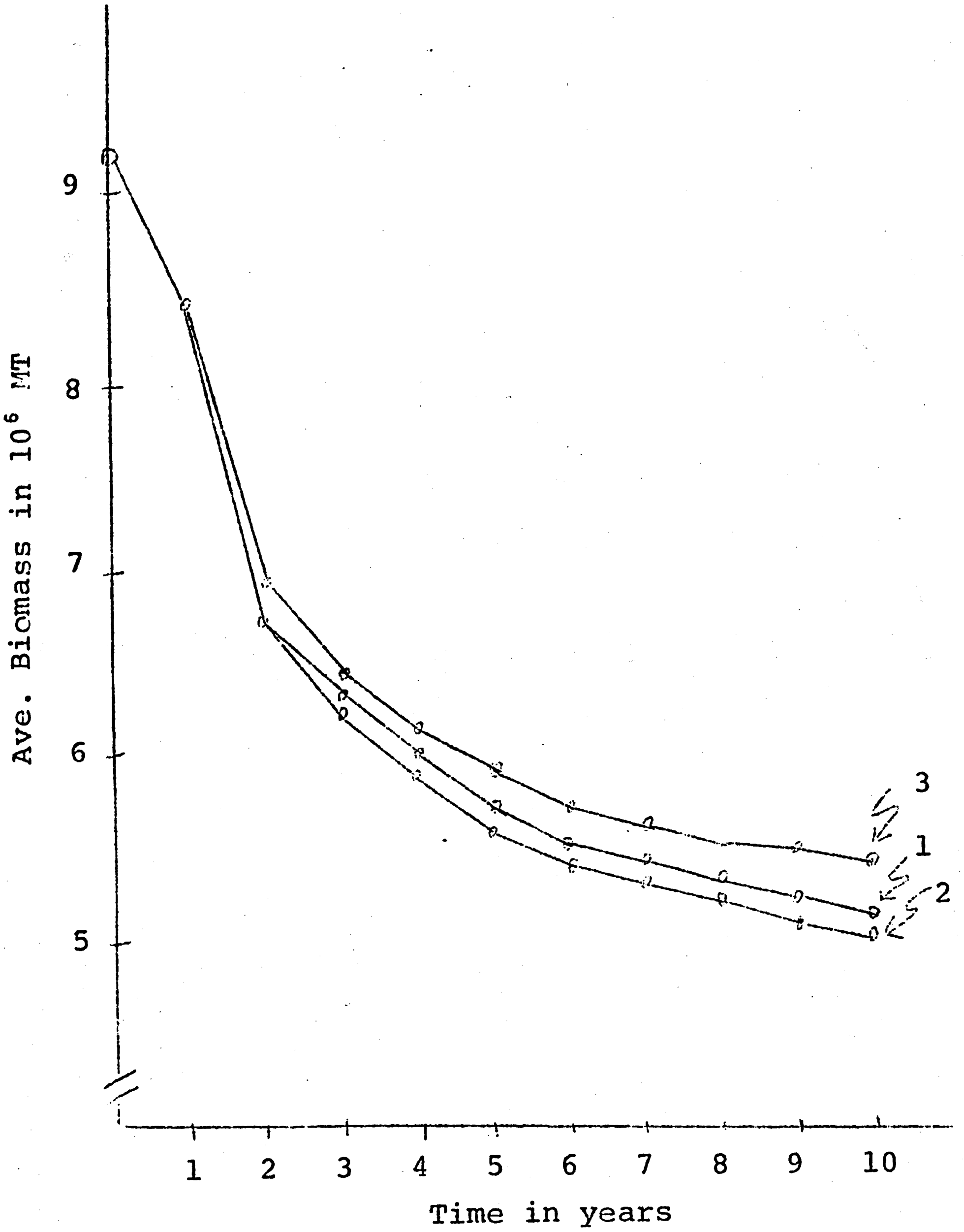


Figure 9 - Behavior of the unfished northern anchovy population given 3 different stock-recruit relationships and an initial population size twice normal.

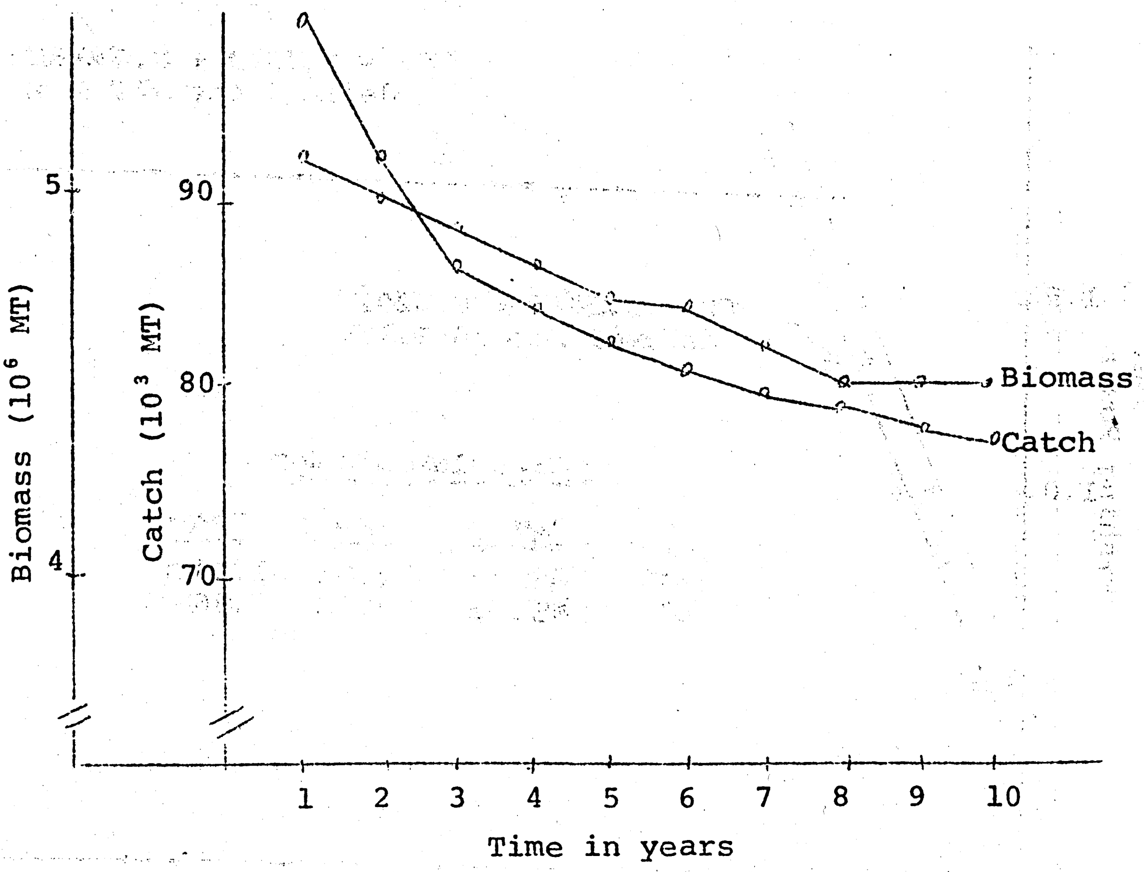
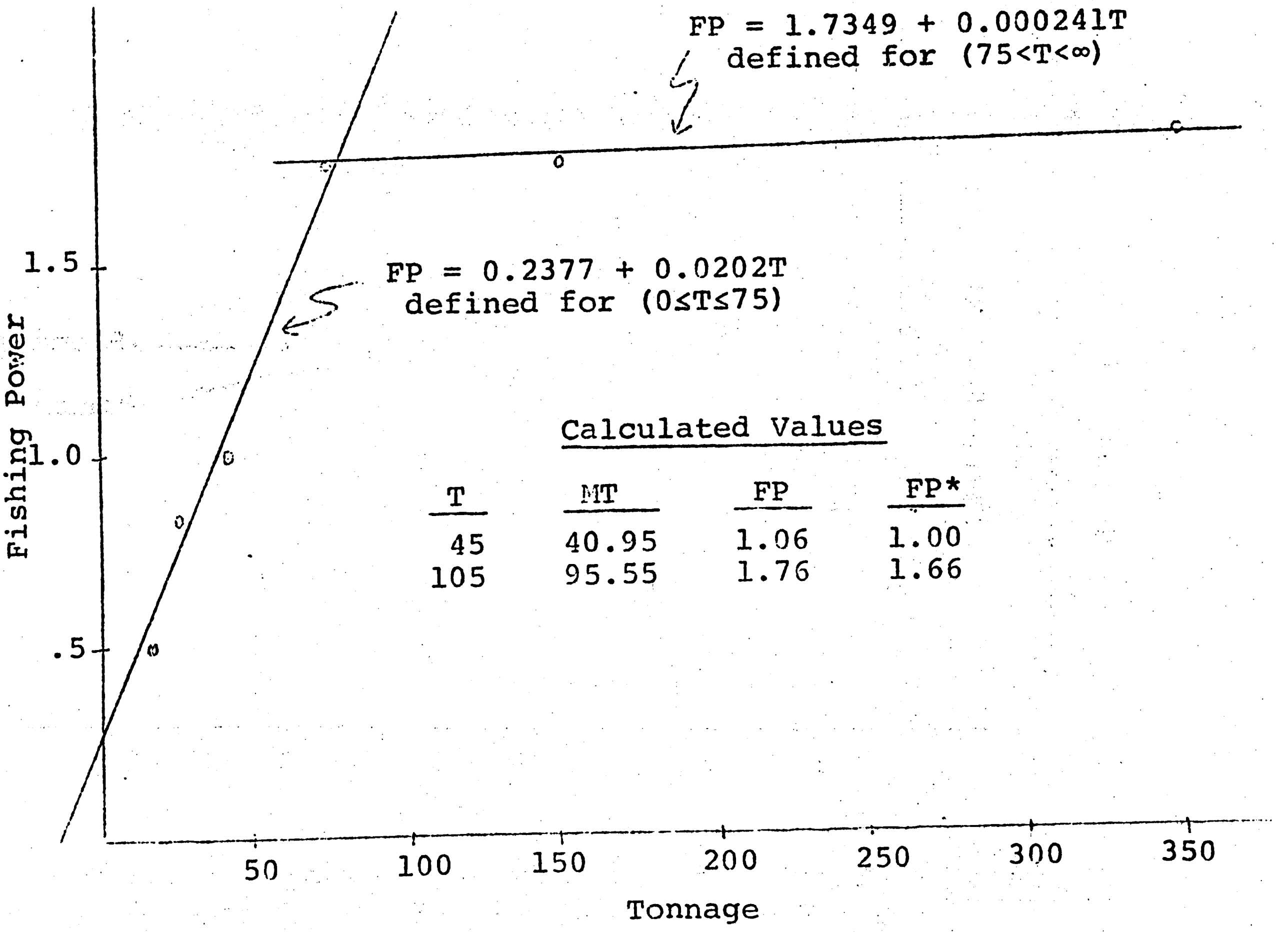


Figure 10 - Behavior of the northern anchovy population given the current fishery (20 vessels averaging 100 MT capacity, an 8 month season beginning in September, 18 days fished per month) and stock-recruit curve 1.



Calculated Values

T	MT	FP	FP*
45	40.95	1.06	1.00
105	95.55	1.76	1.66

Figure 11 - Relation between fishing power and tonnage of Japanese purse seiners fishing for *Trachurus japonicus* (Mitani and Ida, 1965).

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