DEVELOPMENT AND EXAMPLE APPLICATION OF A SIMULATION MODEL OF THE NORTHERN ANCHOVY FISHERY

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ABSTRACT

A computer simulation model of the reduction fishery for northern anchovy, *Engraulis mordax*, is described. The biological subroutine of this model is an age-structured paradigm which is modified to account for age-dependent exploitation and variable recruitment. To demonstrate the model's utility, two example applications are presented which provide insight into the problems of evaluating alternative regulations while lacking perfect knowledge of economic or biological behavior. The model's current value lies in its use as a tool to identify research needs.

Based upon the systems analyses of Tillman (1972) and Stadelman (1974), it appears that the northern anchovy, *Engraulis mordax* Girard, constitutes one of the largest latent fishery resources available to American flag vessels. Relative to its estimated biomass, only a minute fraction of this species is harvested when compared, for example, to catches taken by the fishery for Peruvian anchoveta, *E. ringens*. The present northern anchovy fleet consists of only a small number of relatively old vessels, and the processing capacity of the fish meal plants servicing this fleet is quite inadequate. Thus, unlike many major fisheries of the United States which are marked by overexpansion and overcapitalization, the northern anchovy fishery is still underdeveloped.

According to the above authors, this lack of development can be attributed to a variety of natural and artificial barriers. The natural barriers comprise those constraints over which man has little or no control, including lack of predictive ability concerning the short-term behavior of the market for fish meal. Moreover, there presently is lacking definitive biological knowledge concerning the inherent variation in size and availability of the northern anchovy population, its dynamic stock-recruit feedback mechanisms, and its natural mortality processes. These gaps provide the context of a dynamic and variable environment within which this fishery system operates and with which its managers must contend.

The artificial barriers, on the other hand, are institutional constraints which man has imposed upon the system. While the intent of these rules or regulations may be to govern the activities of fishery participants, their overall effect, in the opinion of Tillman (1972) and Stadelman (1974), has been to thwart economic development of the fishery. For example, small quotas for reduction purposes are intended to prevent overcapitalization of the fishery but have also acted to hinder the much needed replacement and renovation of antiquated reduction equipment. Other artificial barriers and their apparent effects, as perceived by the foregoing authors, include the following: areal and temporal closures to protect stocks, but which act instead to reduce harvest efficiency; union rules to maintain employment levels, but which in fact work to prevent use of technological innovations that would reduce harvesting costs or increase efficiency; landing taxes of $2 per ton to pay for research and management, but which in fact act to reduce substantially the returns obtained by private interests.

If an appropriate goal for decision makers is to foster economic development of the northern anchovy fishery, then the above institutional barriers would seem to present opportunities for achieving that goal. Consequently, a computer simulation model has been developed which provides the means for evaluating the biological and economic consequences of changing various regulations governing this fishery. The purpose of this study is to briefly describe this simulation model and to present two examples of its application which demonstrate some of its utility. These applications focus on the evaluation of alternative regulations when given imperfect knowledge of biological or economic behavior. Finally, the

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value of modelling this system is discussed, taking into account some of the present model's limitations and shortcomings.

DEVELOPMENT OF THE SIMULATION MODEL

General Description

The basic model of the northern anchovy fishery is formulated in terms of GAMES, the general-purpose simulator of resource use systems developed by Gales (1972). This Fortran IV program has been designed to simulate the activities of major sectors involved in the harvesting and marketing of renewable resources. The sectors modelled by GAMES include locations, stocks, harvesters, processors, regulators, products, and markets.

A specific system such as the anchovy fishery (Figure 1) is modelled by indicating, through appropriate inputs, the number of entities in each sector and their logical linkages. The user must also provide the values of parameters which define system processes and structures and the initial values of variables which describe systems behavior. Tillman (1972) provides a detailed listing of the values required for the northern anchovy model. Through appropriate control values, the user also specifies that certain built-in decision routines be used or else provides algorithms of his own design by adding subroutines to GAMES or by modifying existing ones. The user must also provide an appropriate biological model of the stocks being exploited by the harvester-processor sectors.

The main GAMES program resembles the partial listing given in Figure 2. The "Labelled COMMON Blocks" reserves sections of memory for storage of the values of parameters and variables used in common by the 11 subroutines. Subroutine TAPEIN is called first and reads in the initial values of these parameters and variables, including the starting and ending years of simu-

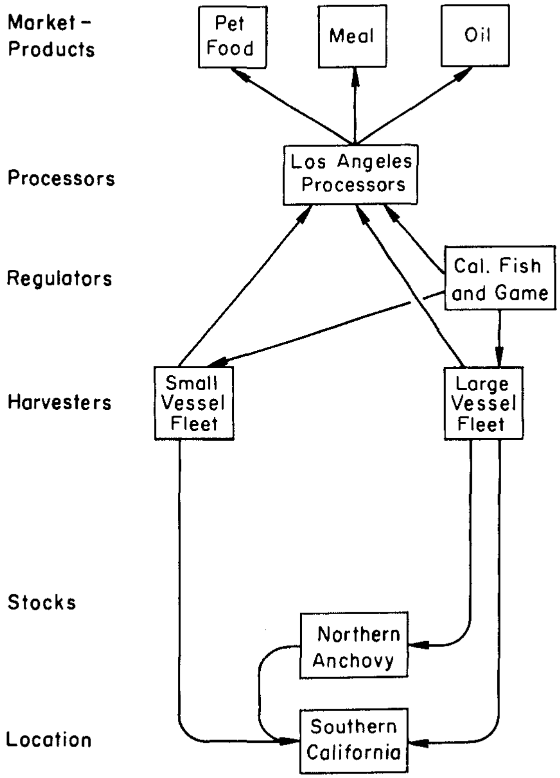

FIGURE 1.—Graphic representation of logical relations between sectors of the present northern anchovy fishery. From Tillman (1972).

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          PROGRAM MAIN

          [Labelled COMMON Blocks]

          CALL TAPEIN

          DO 110 YEAR=NYEAR1, NYEAR2

          DO 100 MONTH = 1,12

          CALL    PROCS

          CALL    HARVS

          CALL    REGLS

          CALL    STOCKS

          CALL    HRVST

          CALL    RMARKT

          CALL    PRCES

          CALL    CMARKT

          CALL    STATS

          CALL    SMSTAT

      100 CONTINUE

      110 CONTINUE

           [Coding for Subroutines]
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FIGURE 2.—Partial listing of the main GAMES program.

lation. The succeeding 10 subroutine call statements are imbedded within a double "do-loop" which is indexed by month and year. This double loop is the principal timing mechanism of the program. Hence, each of these 10 subroutines is executed once a month in the order indicated and either simulates a component of the system, their interactions, or else produces output.

Subroutines PROCS, HARVS, and REGLS make programmed monthly decisions for the system's respective processors, harvesters, and regulators. PROCS and HARVS simulate monthly decisions concerning the processing capacity committed, the number of days spent harvesting, the number of harvesting units committed, and the gear efficiency per unit. Moreover, since processors have only limited storage capacity for raw materials, HARVS adjusts allowable vessel capacities as if processors were establishing boat quotas (a situation presently occurring in the reduction fishery); this prevents overfishing and the consequent dumping of excess catches. REGLS compares these decisions to standards (regulations) supplied by the user or determined by the subroutine. If regulations are "broken," the subroutine makes appropriate adjustments to the values of those parameters associated with improper decisions.

STOCKS is a user supplied subroutine which simulates the biomass dynamics of the exploited resource on a monthly basis. The northern anchovy subroutine is an age-structured model which accounts for the processes of growth, mortality, graduation, and reproduction for each of the seven age-groups (ages 0-6) comprising the population. The basic mathematical theory for age-structured models is treated by Ricker (1958) and Beverton and Holt (1957). This basic theory has been modified to account for age-dependent exploitation and variable recruitment processes in the northern anchovy population. Similar age-structured models have been developed in recent years for other species by Tillman (1968), Walters (1969), Fox (1973), and Francis (1974).

Described further in an ensuing section, STOCKS feeds catch values to HRVST, the subroutine which then simulates the monthly harvesting process. HRVST determines the catch of each stock by a harvester, his harvest proportional costs, and the cumulative catch taken from each stock.

RMARKT then simulates the sale of the harvesters' catches to the processors, and PRCES transforms these newly purchased raw materials into finished goods which are added to the processors' inventories. Subroutine CMARKT then simulates the sale of these products on the open market to final consumers. The quantities demanded are determined from a user supplied demand curve and a sales price set by the processor.

STATS then computes and outputs financial statements for the processors and harvesters. It also provides physical reports describing through key variables the activities of the harvester, processor, stock, and market sectors. Subroutine SMSTAT then provides user desired cumulative physical reports. Although all reports may be provided at monthly intervals, printout typically is suppressed until the year's end.

The Biological Sector

Some Important Assumptions

Development of the biological model for northern anchovy depends critically upon two assumptions. One concerns the stock structure of this population and the other, its stock-recruit behavior. The following discussion briefly examines how reasonable these assumptions are and hopefully provides some justification for their application.

Mais (1974) and Tillman (1975) review the evidence which generally supports the hypothesis that three distinct stocks exist within the northern anchovy's total geographic range. The simplifying assumption has been made that the reduction fleet fishes exclusively upon that stock which resides in the southern California-northern Baja California region of the California Current system. Results of tagging studies indicate that some mixing of adult members of adjacent stocks might conceivably occur due to seasonal north-south migrations (Haugen et al. 1969). However, Mais (1974) cites evidence from comparisons of length-frequency and age-length distributions which, in his opinion, indicates that very little, if any, mixing occurs. Moreover, he concludes that anchovies in this region should be treated as a single biological unit for management (and therefore modelling) purposes.

Several studies (Cushing 1971; Tillman and Paulik 1971; Murphy 1973) suggest that recruitment in clupeid and engraulid populations is a density-dependent process. Moreover, these authors imply that the asymptotic stock-recruit relationship of Beverton and Holt (1957) is generally applicable to populations which have an extended spawning season, whose adults are cannibalistic upon their own young, and whose annual recruitment variations are relatively small. Results from surveys for pelagic eggs and larvae conducted off California indicate that the northern anchovy spawns over virtually the entire year (Ahlstrom 1966). Baxter (1967) stated that this species is a filtering and biting feeder which consumes its own eggs and larvae. Moreover, Murphy (1966) noted that this species has never had spectacularly good nor spectacularly bad year classes and that this may have been a factor in the relatively slow replacement of the Pacific sardine, *Sardinops sagax*, by anchovies following the collapse of the sardine fishery. Consequently, since the northern anchovy apparently fits the required life-style, an asymptotic stock-recruit model does not seem too unreasonable an assumption, although it is an admittedly circumstantial and speculative one at this time.

General Description of STOCKS

STOCKS' main job is to solve the catch equation and pass the result to subroutine HRVST. The following description briefly summarizes the sequence of operations which occur each month and some of the parameter values required to determine the catch in weight for each age group. The details of parameter estimation are given by Tillman (1972).

Following the combined adjustments of PROCS, HARVS, and REGLS, STOCKS first receives the allowed values of the following variables: level of fishing effort (number of vessels), vessel capacity (metric tons (MT)/boat·day), fraction of the month fished, and fishing power of a vessel (Table 1 gives values of relative fishing power for various-sized vessels for which economic performance data are available). These four variables are used to calculate equivalent standard effort, in terms of boats fishing the entire month instead of a fraction of it, and the total harvesting capacity of the reduction fleet.

TABLE 1.—Efficiencies and relative fishing powers of hypothetical vessels operating on northern anchovy. From Tillman (1972).

Vessel capacity		Calculated efficiency	Relative efficiency[1]
Tons	MT		
66	60	0.536	0.681
110	100	0.787	1.000
155	140	1.038	1.319
210	191	1.358	1.726
265	240	1.518	1.929

[1] 100-MT (metric ton) vessel is standard.

Next the age structure is updated by accounting for the process of graduation. Since the great bulk of spawning activity occurs during January-May, most anchovies have their birth dates during these 5 mo. Table 2 gives the proportion of each age-group that is expected to graduate at the start of the months indicated. 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, size of the individual is computed as a weighted average of the sizes of newly entered and residual fish. From these adjusted weights and numbers at age, the biomass of the population is computed.

Contribution to spawning then is calculated for the current month. The number of females eligible to spawn is determined by the proportion of females in the population (Table 3), by a maturity at age schedule (Table 4), and by a schedule of the incidence of monthly spawning activity (Table 5). The egg production of these spawning females is computed by a fecundity at age schedule (Table 6). The results of this procedure are additions to the number of eggs deposited on the stock's spawning ground.

Instantaneous total mortality rates then are

TABLE 2.—Probabilities of graduating from one age group into the next for northern anchovy. From Tillman (1972).

Birth date	Proportion graduating	Cumulative proportion
January	0.17	0.17
February	0.18	0.35
March	0.25	0.60
April	0.25	0.85
May	0.15	1.00

TABLE 3.—Estimates of fraction of females by number in the total northern anchovy population.

Source	Estimate	Source	Estimate
Clark and Phillips (1952)	0.57	Collins (1969)	0.60
Miller et al. (1955)	0.56	Collins (1971)	0.58
Miller and Wolf (1958)	0.52	Average	0.56
MacGregor (1968)	0.56		

TABLE 4.—Maturity at age schedule of northern anchovy. From Tillman (1972).

Age-group	Fraction mature	Age-group	Fraction mature
0	0.10	4	1.00
1	0.40	5	1.00
2	0.80	6	1.00
3	0.95		

TABLE 5.—Incidence of monthly spawning activity by northern anchovy as determined from larval counts. From Tillman (1972).

Month	Fractional occurrence	Adjusted occurrence[1]
1 June	0.10	0.20
2 July	0.05	0.10
3 August	0.03	0.06
4 September	0.01	0.02
5 October	0.02	0.04
6 November	0.03	0.06
7 December	0.03	0.06
8 January	0.11	0.22
9 February	0.20	0.40
10 March	0.17	0.34
11 April	0.17	0.34
12 May	0.08	0.16

[1] Adjusted to insure two spawnings per year.

TABLE 6.—Fecundity at age of northern anchovy, assuming 574 eggs/g body weight. From Tillman (1972).

Age-group	Average weight[1] (g)	Fecundity (eggs/spawning)
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

[1] Average weight in month 10, March, the midpoint of the major spawning period.

TABLE 7.—Age specific catchability coefficients for northern anchovy given different areal restrictions and assuming full recruitment occurs at age 2. From Tillman (1972).

Age	Coefficient when inshore closed (10^{-3})	Coefficient when inshore open (10^{-3})
0	0.24	0.38
1	2.78	4.10
2-6	9.04	9.04

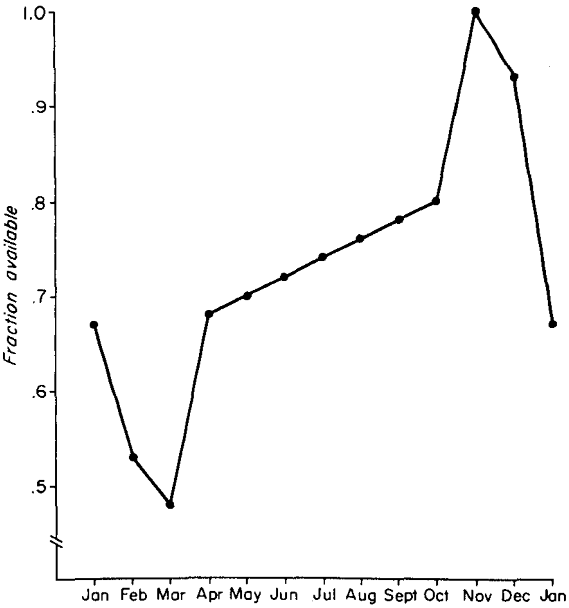

FIGURE 3.—Average monthly availability of northern anchovy in the southern California area. From Tillman (1972).

computed for each age group, which may be subjected to a different total mortality, $Z(A,M)$, depending on natural mortality rate, catchability coefficient, seasonal availability factor, and the total units of standard effort operating upon the stock during the month:

$$Z(A,M) = NM + F(A,M)$$

where NM = constant natural mortality rate
$F(A,M)$ = age specific fishing mortality rate
= $Q(A) \cdot AV(M) \cdot FF(M)$
where $Q(A)$ = age specific catchability coefficient
$AV(M)$ = monthly availability of the stock
$FF(M)$ = standardized level of effort.

According to Schaefer (1967), $NM = 1.10$ and is a constant parameter. Table 7 shows how catchability decreases for ages which are not fully recruited. Figure 3 indicates how availability varies throughout the year, based upon extrapolations of Messersmith's (1969) catch-per-unit-effort (tons/hour) data for two seasons; this seasonal pattern likely is associated with the spawning behavior of adults (Tillman 1972).

Given these mortality rates, the catch of anchovy is then computed for the month subject to the constraint that it may not exceed the reduction fleet's total or assigned harvesting capacity. The fleet and natural mortality at first compete exponentially to determine the number of fish each would take if harvesting capacity were unlimited. The temporary catch in numbers is calculated as:

$$CN(A) = \frac{F(A,M)}{Z(A,M)} \cdot N(A) \cdot EXP$$

where $EXP = 1 - e^{-Z(A,M) \cdot (DT/NCYCL)}$
$N(A)$ = size in numbers of age group
DT = 1 mo

and $F(A,M)$ and $Z(A,M)$ are defined as above. $NCYCL$ is a parameter which determines the accuracy of the solution and typically is set at 4, yielding an effective DT of 1 wk.

The fleet's catch in weight then is temporarily computed as the sum

$$CW(M) = \sum_{A} CN(A) \cdot WT(A,M)$$

where $WT(A,M)$ is current weight at age. If $CW(M)$ exceeds the allowed harvesting capacity of the fleet, $CAPAC(M)$, the catch in weight is adjusted downward:

$$RC = CAPAC(M)/CW(M)$$
$$CW(M)' = \sum_{A} RC \cdot CN(A) \cdot WT(A,M).$$

Also, the fleet is rendered inactive for the remainder of the week.

Fish credited to the harvester in excess of capacity are subjected to natural mortality and then returned to the population. Once the catch cycle has been completed, the number of fish remaining in an age-group is determined by subtracting the numbers caught and the numbers taken by natural mortality.

Growth in length which occurred during the month then is computed utilizing a von Bertalanffy equation (Beverton and Holt 1957). Figure 4 shows the growth in length curve for the following parameter values: $L_\infty = 15.91$ cm, $K = 0.32$, $t_0 = -2.08$. New individual weights at age are then computed from a cubic weight-length relation.

Finally, future recruitment is calculated from the number of eggs deposited on the stock's spawning ground and an egg to recruit survival rate:

$$RECRT(M) = EGGS(M) \cdot SER \cdot SMULT(RATIO)$$

where SER is the equilibrium egg to recruit survival rate and $SMULT(RATIO)$ is a multiplier which adjusts SER in a density-dependent manner. Given Vrooman and Smith's (1971) estimate of equilibrium spawning stock size ($SEQ = 4.55 \times 10^6$ MT), Tillman (1972) estimated equilibrium recruitment ($REQ = 420 \times 10^9$ fish) and equilibrium numbers of eggs ($EEQ = 2 \times 10^{15}$ eggs) to obtain $SER = 0.00021$. The number of new recruits created during the current month will subsequently enter the fishable stock after a prerecruit period of 6 mo.

The appropriate value of $SMULT(RATIO)$ is determined from

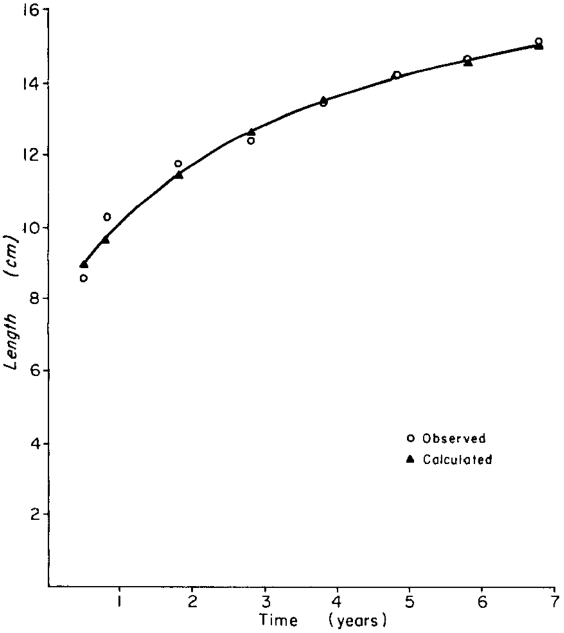

FIGURE 4.—Asymptotic growth in length of northern anchovy. From Tillman (1972).

$$SMULT(RATIO) = \frac{1}{A + B \cdot RATIO}$$

where $RATIO$ provides a measure of the current spawning stock size, $SP(M)$, relative to its equilibrium level, SEQ:

$$RATIO = SP(M)/SEQ.$$

This formulation insures that the stock-recruit process behaves in an asymptotic manner, as has been assumed.

Although data are lacking to estimate specific values for stock-recruit parameters A and B, sets of arbitrary values can be determined by defining a family of curves which pass through the same equilibrium point (SEQ, REQ). Following Tillman (1972), a unique curve in this family is distinguished by its asymptotic level of recruitment, $RMAX$, which can be defined as some multiple of the equilibrium level of recruitment:

$$RMAX = MULT \cdot REQ.$$

A particular set of stock-recruit parameters can then be determined as

$$B = 1/MULT \qquad A = 1 - B.$$

Vrooman and Smith's (1971) larval data provide a rough measure of variation in recruitment during 1962-66, a recent period of population stability. Comparison of their largest index of larval abundance (63×10^{12}) with the mean value during this period (48×10^{12}) indicates that values of *MULT* apparently should not exceed 1.30. Table 8 lists some representative values of *SMULT(RATIO)*, given *MULT* values in the range 1.05-1.20.

TABLE 8.—Egg to recruit survival multipliers *(SMULT)* for a family of three stock-recruit curves passing through the same equilibrium point. A unique curve depends on the value of *MULT* which defines parameters *A* and *B*. Each multiplier corresponds to given ratio between present and equilibrium biomass of the spawning stock.

	Curve	1	2	3
	MULT	1.05	1.10	1.20
	A	0.04762	0.09091	0.16667
RATIO	*B*	0.95238	0.90909	0.83333
0.10		7.00	5.50	4.00
0.20		4.20	3.67	3.00
0.30		3.00	2.75	2.40
0.50		1.91	1.83	1.71
0.75		1.31	1.29	1.26
1.00		1.00	1.00	1.00
2.00		0.51	0.52	0.55
3.00		0.34	0.35	0.38

TABLE 9.—Costs and prices for the northern anchovy model as adapted from Stadelman (1974).

Item	Without power drum	With power drum
Harvesting costs:		
Annual fixed cost/vessel (Depreciation, moorage, property taxes, office and shore expenses, insurance)	$30,126	$30,126
Return on investment (15%)	24,779	24,779
Guaranteed wages (Crew and captain)	132,000 (11)	84,000 (7)
Drum cost (Depreciation and return on investment)	—	6,900
Fixed cost/year	186,905.00	145,805.00
Fixed cost/day fished (Fuel and maintenance)	77.75	77.75
Cost/MT anchovy caught (Net repair)	2.20	2.20
Processing costs:		
Annual fixed cost/plant (Overhead, 15% return on investment)	$150,000.00	
Purchase price of anchovy/MT	25.00	
Processing cost of anchovy/MT	5.50	
Market prices:		
Fish meal/MT	250.00	
Fish oil/MT	110.00	

Some Economic Content

Costs and prices used in this study (Table 9) have been adopted from among those estimated by Stadelman (1974). While these values are dated, particularly with respect to the price increase experienced in 1974, they still serve to illustrate our example applications. Following his suggestion, it is assumed that landing taxes have been removed, that the union has allowed fishermen to receive a guaranteed wage (rather than a share), and that it also has permitted crew size to be reduced on vessels equipped with power drums. Such changes conceivably would permit the fishery to take advantage of new technology that would provide the impetus for its immediate economic expansion. Moreover, it is assumed that quotas have been removed. In their stead, decision makers allow the fishery to expand to its economically optimal level, insuring however that only that fleet size is used and that catch is taken which supplies the optimal level of processing capacity in the system.

These assumptions, particularly the ones pertaining to crew wages and to quotas, may not be very realistic, but they do provide the basis for some interesting modelling applications. Their use infers that the harvesting-processing configurations of this study fulfill three criteria: 1) they maximize net economic yields; 2) they allow for payment of opportunity wages to crew members and of opportunity returns[3] to capital invested in the system; 3) they utilize state of the art technology. Opportunity wages are set at a guaranteed salary of $12,000/man. Also, a 15% rate of return is used to compensate an investor for his loss of alternative uses of capital, for his risk, and for his managerial skill.

State of the art technology implies the use of new plants and new vessels. According to the above study, a new plant has only limited storage capacity for raw materials, a processing capacity of 20 tons/h, and conversion factors of 0.20 for meal and of 0.01 for oil. By working 20 h/day, 252 days/yr, such a plant could process 92,000 MT of anchovy annually. The above study also found that a 210-ton (191-MT) purse seiner was the most economically efficient harvesting unit. A new vessel of this size could be equipped with a power drum, which would lead to a reduction in crew size (from 10 to 6 men) but not necessarily to an increase in harvesting efficiency.

Stadelman (1974) indicated that prices of fish

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[3] One who invests labor or capital in a particular economic opportunity should at least earn that amount which might be returned by his next best investment alternative. The amounts that could have been earned from this second choice are termed opportunity returns; i.e., opportunity wages should be earned by labor and opportunity returns by capital.

meal and oil in the United States are established primarily by the world market for these products. Consequently we have assumed that northern anchovy processors can only accept the prices offered for their meal and oil, rather than being able to affect the world market through their own efforts. In this case, demand curves for their products are nonexistent, and the fixed prices given in Table 9 hold throughout a given simulation experiment.

APPLICATIONS OF THE MODEL

Analytical Technique

Nature of Results

Due to the rough nature of many of the estimates utilized by the model, little credence has been attached to the absolute values of economic return, catch in weight, or population size obtained in the following simulation experiments. These results are at best only informed extrapolations, and, even though their values are of the proper orders of magnitude, it is not the intent of the following applications to accurately predict future returns, yields, or sizes. Of greater importance are the relations between values obtained in different experiments. Consequently, the results have been analyzed on a comparative rather than an absolute basis.

Criteria for Comparisons

The primary results obtained from each experiment include the net economic return (before income tax) generated annually by the entire system, the number of days fished each season, the annual catch in weight, and population size in terms of annual average biomass. In most experiments, these four variables satisfactorily measure the economic and biological performance achieved during an experiment. In preliminary long run equilibrium experiments, values of these variables stabilized within a 10-yr period. Thus, 10 yr has been chosen as the length of all experiments.

Differences between various experiments are measured primarily in terms of the differences between respective net economic returns. Net economic return is obtained by subtracting amalgamated harvester-processor costs from amalgamated gross revenues at the end of each year of simulation. Amalgamated costs include the annual opportunity costs of labor and capital.

Alternative Regulations and Stock-Recruit Sensitivity

Recalling the spectacular decline of the sardine fishery during the 1950's and fearing a similar debacle over another forage species, sportsmen and bait fishermen have become allied in sponsoring state legislation to limit commercial development of the northern anchovy. As a consequence of their efforts, the reduction fishery has been plagued by low quotas and currently cannot fish during the summer (15 May-15 September) nor within 3 miles (4.8 km) of shore. These two specific exclusions define areas wherein tradeoffs might be made to gain concessions from the sport and bait fisheries. Decision makers might retain the summer or inshore closures intact to placate the nonindustrial groups and receive in trade the concession of larger quotas for industrial use of anchovy. Some idea of what is lost by such trades might be obtained by contrasting these closures to others wherein more lenient measures were enforced.

Some evidence exists which indicates that considerable gains in harvesting efficiency might be achieved by lengthening the season to a year or by opening the inshore area. In Figure 3, the pattern of availability extrapolated for May-September indicates that an improving trend is expected during the summer. Also, Tillman's (1972) analysis of age-specific catchability revealed that age-groups 0 and 1 tend to be more available in the inshore area than in the offshore commercial fishery area; he subsequently calculated catchability coefficients reflecting this apparent areal difference (results given in our Table 7).

Using these catchability coefficients implicitly assumes that older anchovies (ages 2-6) are equally available in the inshore and offshore areas. As indicated in Figure 3 we have, of course, attempted to account for the seasonal availability of older anchovies as related to their spawning behavior, but the net result of spawning movements might also tend to distribute older fish farther offshore than younger ones. This circumstance would effectively reduce the inshore catchability coefficient for older fish.

Unfortunately, data on the areal distribution of age-groups, such as the age compositions of catches taken at varying distances from shore, were not available to examine this possibility in detail. However, Messersmith et al. (1969) reported that, during summer and fall echo-sounder surveys, all sizes of anchovies were found concentrated close inshore. Since all sizes were encountered, we speculated that, if fishing were allowed inside of 3 miles (4.8 km), the catchability coefficient for older fish would become reduced only if effort concentrated on or very near nursery grounds, which occur on shallows and flats inside of 50 fathoms. Although lower fuel costs might dictate such a concentration, we further speculated that enforcement of the current minimum size limit of 10.8 cm would make fishing this far inshore unattractive and thus curtail it.

Given these speculations, simulation experiments were conducted in our first application to examine the biological and economic consequences of opening the inshore area to commercial fishing and of allowing a 12-mo fishing season. These were contrasted to a "present" situation consisting of a closed inshore area and an 8-mo season (15 September-15 May). Moreover, sensitivity of the model to changes in the stock-recruit relationship was examined given alternative areal-seasonal restrictions. Stock-recruit curve 2 (Table 8) was arbitrarily chosen as the standard for comparison in these experiments. Each experiment thus determined how an optimal harvesting-processing configuration (numbers of vessels and plants) defined for curve 2 performed when stock-recruit curve 1 or 3 were in effect. Essentially, then, each experiment simulated the decision-making problem wherein a manager assumes that a given biological situation is "true" and plans to meet it but then encounters a completely different situation.

The results of this first group of sensitivity experiments are indicated in Table 10. The main criteria for comparing performances under different stock-recruit curves are the absolute and percentage differences in net economic returns indicated in the last two columns of this table. In all cases, relative to curve 2, harvesting-processing systems performed better under curve 1 and worse under curve 3. As seen from the larger returns, catches, and biomasses generated and from the fewer days of fishing required, curve 1 defined a more productive biological regime relative to curve 2. Likewise, from the smaller returns, catches, and biomasses and from the generally greater number of days of fishing required, curve 3 defined a less productive biological regime.

The economic consequences of imposing different regulatory schemes can also be determined from Table 10. Opening the inshore area would generate about a 30% improvement in net return. Given our assumptions, such an increase is likely due to the increased availability of 0's and 1's which in turn leads to greater catches for the same level of effort. On the other hand, a change in season length would generate an improvement in returns of 120-130%. Quite obviously, from an economic viewpoint, the model indicates that the preferable management scheme would be a change to the 12-mo season. Barring that, the next best scheme would be to open the inshore area.

However, these economic findings should be tempered somewhat by sensitivity considerations. Comparison of areas within seasons (Table 10) reveals that an open inshore area is less sensitive to changes in stock-recruit relations than is a closed inshore area. That is, the percentage change in net returns is less for both curves 1 and

TABLE 10.—Sensitivity of optimal configurations to changes in stock-recruit curves and areal restrictions, given M = 1.10 and deterministic availability.

Length of season	Area	Stock-recruit curve	Fishing time	Average biomass (10^6 MT)	Catch (10^3 MT)	Net return (10^6 dollars)	Difference Absolute	Difference %
8 mo	Inshore closed	[1]2	144	3.92	491.4	6.010	—	—
		1	144	4.00	501.6	6.456	0.446	7.42
		3	144	3.81	477.5	5.408	−0.602	−10.02
	Inshore open	[1]2	141	3.87	537.1	8.014	—	—
		1	140	3.96	547.1	8.454	0.440	5.49
		3	142	3.75	523.9	7.432	−0.582	− 7.26
12 mo	Inshore closed	[1]2	216	3.47	831.9	13.660	—	—
		1	215	3.57	870.5	15.341	1.681	12.31
		3	216	3.32	796.9	12.136	−1.524	−11.16
	Inshore open	[1]2	212	3.43	920.6	17.545	—	—
		1	209	3.63	941.2	18.466	0.921	5.25
		3	214	3.26	886.1	16.024	−1.521	− 8.67

[1] Situations used as standards for comparative purposes.

3 when the inshore area is open, greater when it is closed. Also, in three of four comparisons of seasons within areas, an 8-mo season is less sensitive to changes in stock-recruit relations than is the 12-mo season.

The greater sensitivity of the 12-mo season is probably due to the greater level of effort exerted (e.g., compare days fished) which would tend to drive stock size down into more critical regions of the stock-recruit curve and give rise to density-dependent responses greater than those observed under the 8-mo season. From a sensitivity viewpoint then, harvesting-processing operations planned for the 12-mo season or closed inshore area would tend to suffer most from the present lack of knowledge about stock-recruit behavior; the 8-mo season or open inshore area would tend to suffer least.

Considering our premise that trade offs might be made between quotas and areal-seasonal restrictions, the above model results imply that giving up (trading off) an increased season length represents a considerable loss of potential economic benefit. Such a trade off would therefore seem to require substantial compensation in the form of increased quotas. Trading off a change in areal restrictions, on the other hand, would seem to provide considerably less bargaining power. Moreover, opening the inshore area appears to offer distinct advantages, not only in terms of moderately increased net returns, but also in the form of somewhat decreased operating risk given a lack of biological knowledge. Consequently, the model indicates that trading off a change in season length appears to be the most advantageous tactic for plant and fleet managers if they seek increased quotas.

Technological Change and Employment

In their study of the San Pedro wetfish[4] fleet, Perrin and Noetzel (1970) estimated that the number of jobs on vessels had decreased from 381 in 1963 to 238 in 1968. The figures reflected a reduction not only in the size of the fleet but also in the size of crew as well. In 1963 the average crew size was 10.29 compared to the 1968 average of 9.52. With such a decline in employment, it is not surprising that the union opposes the introduction of technology which would replace more men (Stadelman 1974).

According to Hester et al. (1972), the application of a power drum to purse seining by the wetfish fishery would significantly reduce the size of the crew. Based upon the foregoing author's experiment with a 100-ton (91-MT) capacity vessel, Stadelman (1974) estimated that for a 210-ton (191-MT) purse seiner the introduction of a power drum would reduce the crew from 10 to 6. This would result in significantly reduced vessel operating costs (Table 9) which might allow fleet expansion and a subsequent increase in the overall level of employment. Simulation experiments were therefore conducted to see if a favorable outcome resulted which might dissuade the union from opposing such technological innovation.

Table 11 lists the results obtained for a 12-mo season for both the normal and the power drum methods of purse seining. Use of the drum increased net yield by 80% and the optimal level of fishing effort by 38%. However, the optimal total labor force was reduced from 544 required to man the fleet to an estimated 459. Consequently, the added vessels did not make up for the reduction in crew size.

However, it should be noted that even with the use of the power drum the level of employment would exceed its 1968 level of 238 men. It is also apparent that the additional net yield associated with the power drum, some $2.6 million, might be negotiated into a wage above $12,000. On the assumption that 459 men would be employed, each could receive an additional $5,664/yr and the fishery would still yield the same annual net return as before the innovation. Alternatively, the increased net yield could supply income to employ 215 workers in other activities at the $12,000 wage, whereas prohibition of the power drum would save only 85 jobs in the fishery. This is the type of trade off that must be weighed in determining policy to increase the level of employment.

TABLE 11.—Effect of power drum on employment for a yearlong season.

Power drum	Net yield (millions)	Level of effort (standard vessels)	Labor force	Total gross wages paid (millions)
Without	$2.9	49	544	$6.5
With	5.5	68	459	5.5

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[4] Wetfish are defined by Perrin and Noetzel (1970) to include northern anchovy for reduction; and Pacific sardine, jack mackerel, *Trachurus symmetricus*, chub mackerel, *Scomber japonicus*, and Pacific bonito, *Sarda chiliensis*, for canning and the fresh-fish market.

The foregoing results assume that the physical efficiency of harvesting is not increased by the power drum. The study by Hester et al. (1972) revealed that the use of a power drum and fish pumps to unload the nets often enabled the experimental vessel to get in an extra set during the brief time fish were available before dawn. This circumstance depended on the size of catches being made since use of the equipment actually increased the set time for very small catches. No data were presented, however, as to the average number of sets or the frequency of catch size for evaluation of efficiencies.

The above analysis points up the importance of union work rules permitting the use of new technology. The application of the power drum to vessels apparently would improve the economic viability of the fishery, permitting its operation even with old hulls or at fish meal prices below $250/MT. Although use of the drum reduces crew size on an individual vessel, its general adoption apparently would provide considerable economic incentive for fleet expansion, leading to an increase in overall employment beyond its 1968 level.

To make this inference, however, we have assumed away the real problem, which is not the adoption of new technology but the alteration of traditional union share agreements which pay the crew a percentage of net revenues. Unless new technology resulted in increased gross revenue as well as a reduction in crew size, the same share of the net revenue would simply be divided among fewer crewmen, and the investor would gain nothing to compensate him for the additional costs of the technological change. Consequently, the present system does not allow the investor a sufficient return, and the fishery suffers in terms of employment levels as well as with respect to economic efficiency.

DISCUSSION

In discussing his model of the ecological bioenergetics of isopods, Hubbell (1971) indicates that there is a twofold utility in modelling a given system. First, the model can be regarded as a tool to guide and orient future research on that system. Second, once the model exhibits satisfactory performance, it can be put to predictive use, answering hypothetical questions about the consequences of different input conditions upon system behavior. As demonstrated by the preceding applications, we feel that the northern anchovy model definitely has the potential for fulfilling both of these purposes.

However, in its current state of development the model is admittedly speculative in some of its content. Several of its shortcomings have already been discussed, but perhaps its greatest failing is that its behavior has not yet been adequately validated. To do so would currently require the circular logic of testing the model against the very data from which its assumptions and estimates derive. Consequently we have been forced to rely upon our own subjective view of what constitutes well-behavedness in the model and have applied this criterion in evaluating its performance.

According to Patten (1972), we probably could do little more to validate the model since there currently exists no theoretical base for approaching this fundamental modelling problem. In any regard, the predictive use of this model should therefore be treated in only the most general of terms, i.e., with the aim of gaining insight into the structure and behavior of the anchovy fishery. In this sense, it presently is a conceptual rather than an analytical model.

This leaves its use as a tool for guiding and planning research as the model's primary reason for being. To that end it has proven quite useful, providing a systematic means by which extant data might be organized and pinpointing areas characterized by a glaring lack of data. For example, our approach to modelling stock-recruit behavior was necessitated by a lack of appropriate indices measuring recent stock and recruitment sizes.

Additionally, we feel that the model provides the capability for identifying and ranking critical research areas. Management decisions must be timely and as correct as possible, yet the cost of collecting and analyzing relevant data is very high both in money and time. Given budgetary constraints, all research needs cannot possibly be satisfied. Therefore, decision makers should be asking themselves whether the cost of better information will be justified by a better choice of management policy.

The model could play an important role here by allowing the decision maker to test the sensitivity of his information upon policy alternatives. Some policy sets will not be affected by slight changes in estimates resulting from fuller information: a somewhat higher growth rate than initially believed, for example, may not occasion any revision in policy. The degree of sensitivity thus determines which information is trivial and which is critical. Parameters of the model which prove to have little or no effect on the decision then need not be refined by further research.

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