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THE MIT SINGLE-SPECIES FISHERY SIMULATOR: APPLICATION TO THE GEORGES BANK YELLOWTAIL

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APPLICATION TO THE GEORGES BANK YELLOWTAIL**

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RELATED REPORTS

The following reports contain information related to the project described herein:

Devanney, John W., III. MARINE DECISIONS UNDER UNCERTAINTY. MITSG 71-7. Cambridge, MD: Cornell Maritime Press, November 1971. 203 pp. \$6.50.

Devanney, John W., III. FISHERMAN AND FISH CONSUMER INCOME UNDER THE 200-MILE LIMIT. MITSG 75-20. Cambridge: Massachusetts Institute of Technology, February 1975. 35 pp. \$1.00.

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CHAPTER 1

INTRODUCTION

1.1 Preamble

This study has two sets of goals:

1. The development and documentation of a fisheries simulator which integrates the dynamics of the stock-recruitment feedback system, our uncertainty as to the exact form of this relationship, and the economic implications for the fish purchaser as well as the fisherman of the resultant dynamic fluctuations under a given management policy. In particular, we intend to use such a model to argue that, apart from a few exceptional cases, fisheries management should not and need not be based on steady-state models. Also, we wish to demonstrate how Bayesian reasoning can be used to incorporate uncertainties as to future recruitment within the model.
2. The application of this model to the Georges Bank yellowtail fishery.

The Georges Bank yellowtail was chosen for the initial application of this model for several reasons:

1. Its importance. The yellowtail is the single largest New England finfishery in terms of revenues. Gross landed revenues have been running about \$20 million per year.
2. Its relative simplicity. For all practical purposes, this is a strictly domestic, strictly commercial

fishery. Recreational fishing, with its attendant data and economic valuation problems, is not important. The fishery is, and has been for some time, exploited almost exclusively by Americans operating for the most part from three or four ports. Biologically, the yellowtail is a bottom feeder whose diet consists almost entirely of small crustaceans and mollusks, thereby simplifying predator-prey relationships. For the last five years, practically all domestic yellowtail landings were sold fresh and for the most part consumed within fifty miles of the coast between Boston and New York. Downstream processing is not an important part of this fishery.

3. The available data base is at least as good as that for any non-anadromous fishery.

To put it another way, we tackled the yellowtail first because it was the easiest. If we are unable to obtain useful insights from the model on yellowtail, we can be sure that the effort will fail on other species.

The New England yellowtail fishery is based on two stocks which biologically are almost independent: the Southern New England stock (sometimes designated as "West of 69°W") and the Georges Bank stock (known as "East of 69°W"). The New England Regional Council intends to manage these stocks as separate entities. This report deals strictly with the Georges Bank stock. There are two reasons for this choice:

- A. The Georges Bank stock, being further offshore, is not fished recreationally, nor by commercial day trippers. Hence, landings and effort data are more reliable.
- B. The Southern New England stock is in such abysmal shape that the correct management strategy is obvious: no effort. Southern New England catches have dropped from a high of 35,000 tons in the mid-sixties to three thousand to five thousand tons in the last few years. Juvenile abundance indices have dropped by a factor of sixty in the same period--strong evidence of a stock-recruitment dependency for this species, by the way. In short, the Southern New England stock, from at least the point of view of economics, has been practically wiped out. We do not need a computer to tell us the appropriate management strategy is zero effort and indeed, the New England Council has ruled that there will be no directed yellowtail fishery west of 69°W longitude.

The Georges Bank yellowtail fishery developed somewhat later than the nearer-shore Southern New England fishery. Hence, this fishery is still in a relatively salvageable, if rather unhealthy, state. Table 1.1.1 reviews the recent history. The catch for the last few years has been fairly stable at about 15,000 metric tons per year. However, the catch per unit effort has recently dropped quite sharply from an average of 3.9 tons per day fished in

TABLE 1.1.1
GEORGES BANK YELLOWTAIL FLOUNDER CATCH AND EFFORT STATISTICS

Year	Domestic Catch ^a Thousands of Metric Tons	Foreign Catch Thousands of Metric Tons	Total Days Fished	Landings Per Day Fished	Juvenile Age 1 Abundance Indices
1963	16.6	0.1	3,071	4.6	11.60
1964	19.8	--	3,575	5.6	2.64
1965	18.4	0.8	4,569	4.1	1.29
1966	13.4	0.3	5,820	2.4	9.76
1967	13.9	1.4	3,501	3.7	6.96
1968	16.4	1.8	4,266	3.9	10.59
1969	18.5	2.4	6,717	3.1	7.64
1970	21.0	0.3	6,223	3.5	4.75
1971	15.0	0.5	6,082	2.5	3.82
1972	15.3	2.2	8,060	2.2	2.42
1973	16.5	0.3	6,837	2.7	2.71
1974	15.8	1.0	8,078	2.0	3.50
1975	14.5	0.1	8,675	1.7	4.05

^aIncludes discards.

Source: New England Council [1967], Parrack [1976].

the 1970-1973 period to 3.0 tons per day in 1974 and 2.5 tons per day in 1975. Abundance indices computed from research vessel trawl landings also dropped by 50% in this period. More importantly, the age composition of the catch is much too young. The ICNAF Assessment Committee comments:

Age compositions of catches in 1975 indicate a large contribution of age 2 fish, although survey data did not show the increased abundance of this year-class. In view of the abundance of this age-group in the catches, it can be assumed that fishing mortality on it approximately doubled. This is the age-group that the mesh regulation (130 mm. manila) was intended to conserve, because yellowtail double their weight between age 2 and age 3. If higher yields are desired from this fishery, the fishing mortality on two-year-old fish must be reduced [ICNAF, 1976a].

Current fishing mortality is double the "optimum" as computed by almost certainly optimistic models which assume that recruitment is not a function of the level of adult stock. Worst of all, the low level and youth of the standing stock may be affecting recruitment.

The level of recruitment assumed for 1976 and 1977 (42 million fish at age 2) is equal to the lowest level since 1962, as estimated from preliminary virtual population analysis (the mean value for 1962-72 is 56 million fish). The lack of adequate estimates of discards, both in the directed fishery and in by-catches, make the estimation of stock size from virtual population analysis rather inaccurate [ICNAF, 1976a].

Even in the absence of a quota, ICNAF predicted a further decline in the catch to 12,500 tons for the eastern Georges Bank for 1977.

In view of this evidence that the yellowtail stock is in a precarious state, the ICNAF Assessment Committee

recommended a 1977 TAC for the Georges Bank yellowtail of 7,000 tons. For all practical purposes, nobody but Americans fish yellowtail on the Georges Bank. The total foreign catch as reported to ICNAF, including Canadians, for 1975 was ninety-two tons. Therefore, if the Regional Council had acted on the ICNAF recommendations, Americans would have had to cut back on their current catch by a factor of two. Instead, the Regional Council compromised on a catch of 10,000 tons, considerably lower than earlier TACS but, according to our analyses, not low enough. According to our analyses, even without a quota, at present levels of effort the 1977 catch will be no more than 12,000 tons, in essential agreement with the ICNAF 1976 estimates. More importantly, our analyses indicate a catch of 10,000 tons will throw the fishery into a severely depressed state and, unless drastic measures are taken, the catch will dwindle to a few thousand tons or less in a few years. The model claims that the cost of this overfishing to New England fishermen relative to optimal management over the next twenty-five years will be about \$5 million per year in net income. The cost to consumers in terms of high prices and forgone consumption will be equivalent to \$6 million annual loss over the same period, although neither group will feel the real impact of such overexploitation for another year or two. The model argues that, if these losses are to be avoided, foreigners must continue to be excluded from the

fishery and present levels of domestic effort must be reduced by a factor of two, and quickly. If entry to the fishery cannot be restricted, then the model feels a quota of 8,000 tons per year--rather close to the original ICNAF recommendations--is required to prevent the stock from declining further. However, the economic losses associated with a quota system as opposed to limiting entry are quite large, as we shall see.*

In short, this report can be viewed as either an academic exercise in further developing fisheries modelling methodology, introducing and investigating several new techniques in fisheries simulation; or as a stopgap attempt to lend technical support to immediate, decisive management measures to save a fishery which we believe to be in real trouble. The authors, of course, would like to think of it as both.

1.2 The need to manage domestic effort

The 200-mile limit has been in force for almost half a year now. Enforcement of the law with respect to distant-water fishermen has proceeded smoothly for the most part. With the exception of one or two species, which are not the focus of this effort, it is now clear that the United States has developed a reasonably effective system for establishing control over foreign fishermen on its continental shelves. In many circles there is a widespread belief that

*This argument assumes that a rigid quota of 8,000 tons can be enforced. Recent experience in attempting to enforce a quota on cod is hardly encouraging in this regard.

the exclusion of the foreigners will by itself solve the problems facing our continental shelf stocks. This position cannot withstand scrutiny on either theoretical or empirical grounds. If the Georges Bank stocks are to recover and if we are to obtain maximum economic value from the stocks, we must not only exclude the foreigners but also develop tight and effective control over domestic effort, at least with respect to the high-value species. To see this consider some recent catch statistics (Table 1.2.1).

Table 1.2.1 lists the Georges Bank/Gulf of Maine (ICNAF Subarea 5) catch for 1973, 1974, and 1975 for the major swimming species. The catch volume numbers are ICNAF figures as reported by the member nations. As such, they are subject to some error. However, these figures are continually reviewed by knowledgeable scientists of all nationalities who have independent data on level of effort by nation, catch per effort, and abundance indices. Therefore, it is unlikely that for the major species these figures contain really large errors.

Table 1.2.1 indicates that in terms of overall volume the foreigners have indeed been taking the great bulk of the total catch. But Table 1.2.1 also indicates that the foreign catch was concentrated in the pelagic species (herring, mackerel) and to a lesser extent in hake. The American catch is focused almost exclusively in bottom-dwelling (demersal) species (cod, flounder). It turns out that the latter species have an

TABLE 1.2.1

COMPARISON OF CATCH VOLUME (TONS) AND GROSS CATCH VALUE (THOUSANDS OF DOLLARS) FOR SUBAREA 5

	Cod/Haddock		All Flounder ^a		Herring ^a		Mackerel ^a		Hake		Totals	
	Volume	Value ^b	Volume	Value	Volume	Value	Volume	Value	Volume	Value	Volume	Value
1973 USA	25,288	14,471	43,998	20,331	29,293	1,736	1,336	88	18,689	1,851	115,604	38,477
Can.	4,900	2,804	112	52	9,190	606	53	3	--	--	14,255	3,465
Oth.	10,387	5,944	3,308	1,528	199,783	13,191	379,775	25,076	151,053	14,961	744,306	60,700
1974 USA	28,527	16,324	43,575	23,977	32,741	2,161	1,042	69	11,522	1,141	117,407	43,672
Can.	2,154	1,232	90	49	4,261	281	0	0	0	0	6,505	1,562
Oth.	8,894	5,089	906	498	149,742	9,887	293,883	19,405	127,383	12,616	580,808	47,495
1975 USA	29,661	20,228	35,077	20,064	35,681	2,354	763	50	17,946	1,776	119,128	44,472
Can.	3,362	2,292	101	57	5,084	335	4	0	2	0	8,553	2,690
Oth.	7,016	4,784	1,033	590	136,969	9,039	166,316	10,976	86,730	8,586	398,064	33,975
Total USA	83,474	51,023	122,650	64,372	94,715	6,251	3,141	207	48,157	4,768	352,139	126,621
Can.	10,416	6,328	303	158	18,535	1,222	57	3	--	0	29,313	7,717
Oth.	26,297	15,817	5,247	2,616	486,494	32,117	839,974	55,457	365,166	36,163	1,723,178	142,170

^a Subarea 5 & 6.^b Based on cod. Biased on the low side because haddock was more valuable over this period.

American market value which is roughly ten times that of the former. Current cod values are 20¢ to 50¢ per pound, depending on season and size. Haddock is worth 35¢ to 60¢ per pound, ex-vessel round weight; flounder, 35¢ to 70¢. In contrast, herring and mackerel, which have a very limited foodfish market in the States, are sold to fishmeal processors at 3¢ to 5¢ per pound. A typical price for hake currently is 5¢ to 7¢ per pound.

In Table 1.2.1 we have combined the ICNAF catch statistics with price data to arrive at an estimate of the gross landed value of the catch by country and species using American market prices. For species which are largely caught by Americans we have used low prices; for species which are largely caught by foreigners, we have tended to use high-side prices. For example, the 1975 cod and haddock catch has been valued at 30¢ per pound. All 1975 flounder has been valued at 25¢ per pound. These were roughly the lower levels achieved in the respective categories in the market. On the other hand, hake has been valued at 5¢ per pound despite the fact that if all the foreign catch were landed in the States, the market price would almost certainly be lower than this.

In any event, when one compares the total catch on landed value basis, one reaches a very different conclusion from that based on weight. The simple fact is that the Americans have been and are taking 75% to 95% of the high-value swimming species caught in the Georges Bank/Gulf of Maine area.

One can make an even stronger statement in terms of economic rent. The economic rent associated with a resource is the difference between its gross landed value (the figures shown in Table 1.2.1) and the cost of the resources required to land it. The economic rent to Americans associated with landed herring or mackerel at 4¢ per pound is a small proportion of that 4¢. In other words, an American can't make a great deal of money fishing mackerel or herring at 4¢ per pound, which is, of course, the reason Americans don't attempt to heavily exploit these stocks. On the other hand, as we shall also see, the economic rent associated with landing cod or flounder at 40¢ per pound can be a very significant portion of that 40¢. To oversimplify for the moment, the economic rent associated with landing a pound of herring or mackerel might be (generously) 1¢ a pound. The economic rent associated with landing a pound of flounder can easily be 20¢ per pound. In terms of economic rent, the difference between the low-value and high-value species can easily be a factor of twenty. We shall also argue that economic rent is a better measure of the economic value of an activity than is gross landed value. In short, in terms of economic rent at American market prices, American fishermen were taking the great bulk of the total economic value being derived from the swimming species of the Bank before the imposition of the 200-mile limit.*

*The possibility of marketing herring to the much higher-priced European foodfish market has not been examined in this study, which is almost completely concerned with groundfish. This possibility deserves a thorough study.

The implications of this fact for the future management of the fishery will be one of the central themes of this report.

To anticipate, we will conclude that the Americans currently fishing the principal cash crop of the Georges Bank, the yellowtail flounder, have the ability to destroy the stock by themselves, even without any foreign effort and without any further expansion. In fact, we will argue that current American effort on the yellowtail must be cut back by a factor of two if we are to preserve the stock at anywhere near its optimal level.

Fisheries are a common pool resource. As such, it is an economic truism that they will be subject to overexploitation absent of effective management. This argument, the tragedy of the commons, depends in no way on the nationality of the exploiters. The central issue in American continental shelf fisheries is no longer the foreigner; it's free entry to a domestic resource over which private property rights cannot be imposed.

Even if domestic effort had to expand to regenerate the Free Entry level of overexploitation, we can be sure absent of effective regulation that drawn by the momentary surpluses associated with the expulsion of the foreigners they would. However, in many cases, they will not have to expand very far. On the contrary, in some cases including the economically most important Georges Bank species, there is already much too much domestic effort on our continental shelf stocks.

Obviously, these unhappy facts of life place a very heavy burden on the Regional Councils. In an attempt to lend technical support to the difficult deliberations the Councils face in managing the stocks under their responsibility, MIT has developed a bio-economic fisheries simulation which we called FISHDYN1. The purpose of this report is to describe this model and the results of a series of application to the Georges Bank yellowtail fishery. However, before doing so, we must review a little basic economics. This is the purpose of Chapter 2. Chapter 3 outlines the basic philosophy of FISHDYN1. Chapter 4 describes the model in some detail. And Chapter 5 describes the results of applying the model to the current situation facing the Georges Bank yellowtail stock. Chapter 6 summarizes what we believe we have learned from this analysis.

CHAPTER 2

SOME BASIC ECONOMICS RELATING TO FISHERMEN AND
FISH CONSUMER INCOME2.1 The concept of black-box income

This report analyses the impact of a range of alternative schemes for managing the principal Georges Bank fishery, the yellowtail flounder, on real national income, on real fisherman income, and on real fish consumer income. If we are to perform an income analysis for any particular group, whether it be fish catchers, fish consumers, or the entire nation, we must first define just what we mean by the real income of this group.

One way of developing our definition of a group's real income is to imagine that we have drawn a black box about this group. Every member of society who is a member of the group whose income we wish to analyze is placed inside this black box. Any member of society who is not a member of this group is placed outside this black box. Thus, if we are interested in the income of a particular individual, we draw our black box around this single person. If we are interested in national income, we draw our black box around all Americans. If we are interested in the income of a particular state or town, we draw our black box around the residents of that state or town and exclude everyone else. If we are interested in the income of a particular profession, we draw our black box around the members of this profession and exclude everyone else.

For any black box, we define the total value of all the goods, priced at current market prices, which the inhabitants

of that black box can consume, to be the real income of that black box.

Perhaps the easiest way of getting at the implications of our definition of real black-box income is to imagine that the black box is owned and controlled by a single personage-- Uncle Eph we might call him. Suppose the black box currently under analysis is a particular state. Uncle Eph is the not-particularly-benevolent despot who owns this state. Uncle Eph is interested in the total value, at present market prices, of all the goods he can consume with the output of the rather extensive resources he controls. Uncle Eph realizes that he can allocate his resources in an infinite variety of ways, some of which will allow him to consume a higher total value of goods than others. Uncle Eph, for reasons he chooses not to discuss, would like to make this market value of his consumption as large as possible.

His resources include not only the land and water, the buildings and roads, vehicles and vessels of his state, but also its present human inhabitants. We might regard this latter brand of resources as Uncle Eph's fingers, in that they both produce and consume. Uncle Eph has no particular feelings about his fingers. He isn't interested in whether one finger rather than another consumes a greater share of the total value of all the goods he consumes. He is only interested in the total. He considers himself better off if this total value is larger, worse off if it's smaller, regardless of the distribution of production and consumption among his fingers.

Notice that in attempting to maximize this quantity, Uncle Eph is ignoring the fact that any proposed change in the allocation of his resources will almost certainly make some of his fingers worse off and some better off. Uncle Eph simply doesn't care. He prefers the change if the total value of the consumption of all his fingers is higher after the change than before. He will eschew the change if the total value is less. Our concept of black-box income ignores the distributional effects of any proposed change within the black box.

This limitation has obvious political implications, for what may be a net increase to the black box as a whole can affect a particular set of losers quite adversely. For example, real black-box income will be increased by a change which increases the real income of 90% of the black box's citizens by 10% and decreases the real income of 1% of the population by 70%, virtually wiping out this latter group.

There is another thing to notice about Uncle Eph. His is a provincial and basically selfish character. He only cares about his own ability to consume. He is completely indifferent to any effect, up or down, his choices might have on the income of entities outside the black box--the rest of the country, for example. Any change in income to someone who is not a member of the black box currently under analysis, no matter how large, is given no weight at all by our concept of black-box income.

Paradoxically, the fact that our concept of black-box income ignores the distribution of income changes within the

black box and ignores any income change outside the black box is precisely the characteristic which allows us to think quantitatively about the economic conflicts inherent in fisheries management. To do this we need only analyze the same policy alternative from the point of view of a number of different black boxes sequentially. Analyzing the same policy from the point of view of national income (the black box equals all Americans), then from the point of view of fishermen income (the black box is fishermen), and then from the point of view of fish consumers (the black box is all Americans less the suppliers of fish*), will reveal both where the second and third group have a common interest through their joint memberships in the first group and where they are in direct conflict.

The relationships can be illustrated by the pie analogy. Regard national income as a pie. The size of the pie represents the amount of national income. This income is consumed either by the fishermen or by the public (non-fishermen). In general, different fisheries management alternatives will affect both the size of the overall pie (national income) and the relative share of this income going to the fish supplier and fish

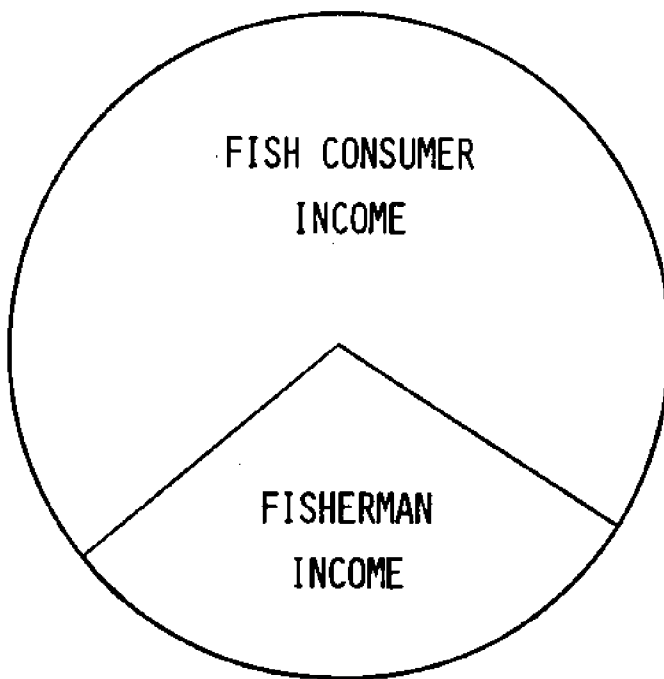
*FISHDYN1 is aimed primarily at the New England demersal fisheries. Almost all of this fish is sold fresh. Therefore the model stops at dock side. It does not simulate downstream processing or retail distribution. Thus in FISHDYN1 fisheries are just that and the fish processor and retailer are lumped with the fish consumer as part of the rest of the nations. In so far as the processor and distributor have market power over the consumer, some of the increase in consumer income associated with landing more fish at lower prices will actually show up in increased profits to processors and retailers. FISHDYN1 is unable to distinguish between increases in consumer income and increases in processor/distributor income.

consumers. Figure 2.1.1 schematically compares two hypothetical alternatives. Alternative A generates a higher national income than B, but B results in the fishing industry obtaining a larger proportion of the smaller pie, so that fish supplier income is actually higher under B than A. Obviously, both groups can theoretically agree to jointly attempt to make the pie as large as possible. After all, in theory a larger pie can always be redivided in such a way that everybody gets a bigger piece than with a smaller pie. But the two groups are in direct conflict when it comes to dividing up any given pie.

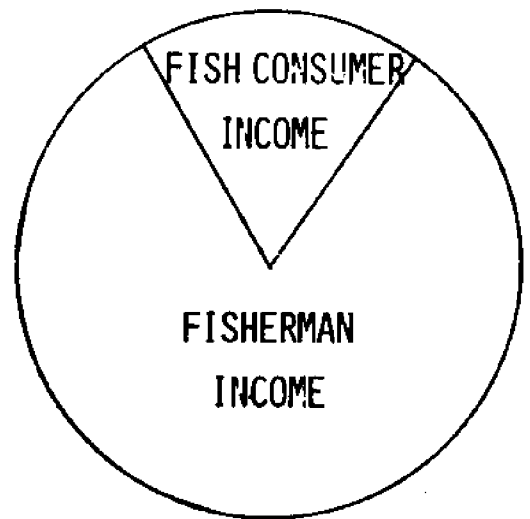
2.2 Fisherman surplus and the common-pool problem

The only justification for this long-winded repetition of tautologies is that quite commonly these fundamentals are ignored in the public debate concerning the fisheries of the continental shelf. Sometimes this debate proceeds as if there were some sort of conservation principle which dictates that the overall size of the pie is fixed, that the amount of national wealth realizable from a particular fishery resource is given and the only question is who is going to get what share of this fixed pie.

The fallacy in this line of thinking can be demonstrated by a simple yield-effort diagram, Figure 2.2.1. This figure sketches a commonly postulated relationship between the amount of fishing effort and landings. The hump represents a situation in which at low level of fishing effort, measured in say boat-days, an increase in effort will increase yield. However, as more and more effort is applied, more and more boats fishing



ALTERNATIVE A



ALTERNATIVE B

Figure 2.1.1--The pie analogy.

the same stock, the increase in yield with increase in effort drops off until at point MSY a peak yield is obtained. The level of landings at this point is known as the Maximum Sustainable Yield. Beyond this point, an increase in effort will actually decrease total landings as the decrease in population age and numbers associated with this additional fishing effort more than outweighs the additional fishing effort.

Assuming a competitive landed fish market, associated with any particular level of landings will be a market clearing price. The demand curve in Figure 2.2.1 hypothesizes such a relationship between amount landed and the price that amount can be sold ex-vessel. In the curve shown, we have postulated lower and upper limits to prices at very high and very low levels of landings respectively, but in between there is a region in which moderate changes in landings can have a large impact on price--qualitatively not unreasonable assumptions for New England premium fresh fish markets, as we shall see.

It is a simple matter to combine Figures 2.2.1 and 2.2.2 to obtain Figure 2.2.3, which plots fisherman revenue against fishing effort. Fisherman revenue is simply yield times the market price at that yield. Assuming market price decreases with an increase in landings, the revenue curve will be steeper than the yield curve at low yields and less steep at high yields. Further, if the demand curve is inelastic at moderately high landings, as the one in Figure 2.2.2 is, then in the vicinity of the Maximum Sustainable

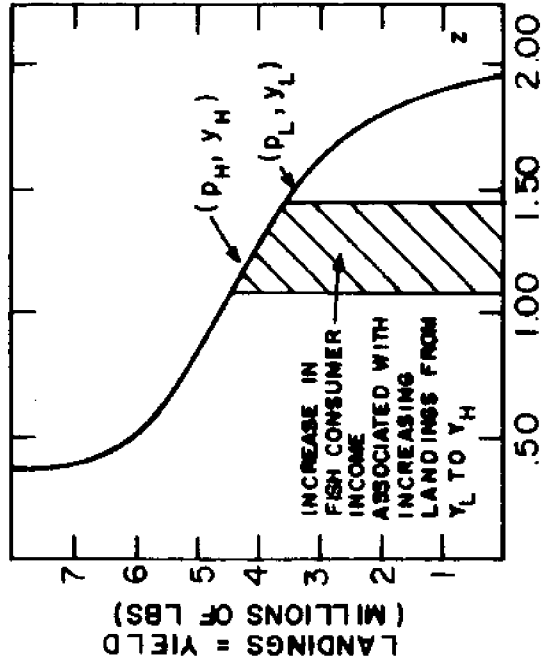


Figure 2.2.2 Landings vs landings.

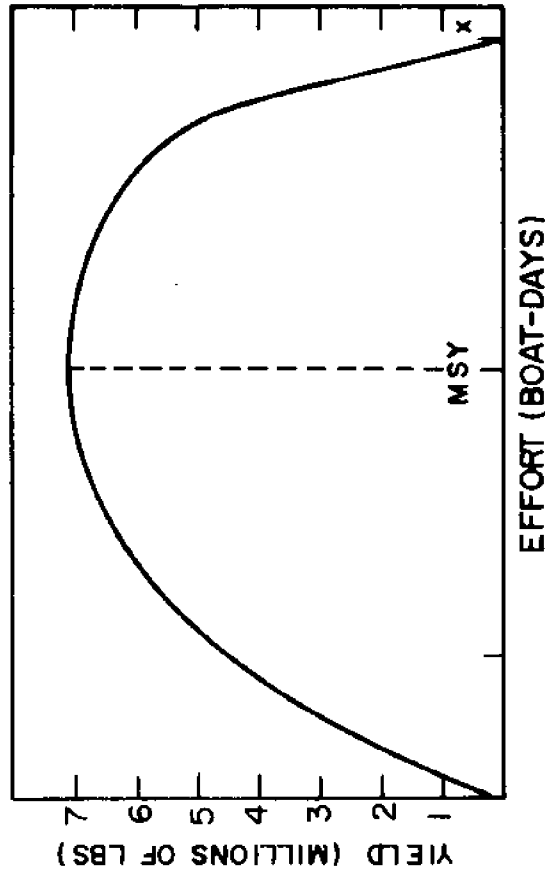


Figure 2.2.1 A hypothetical-effort relationship.

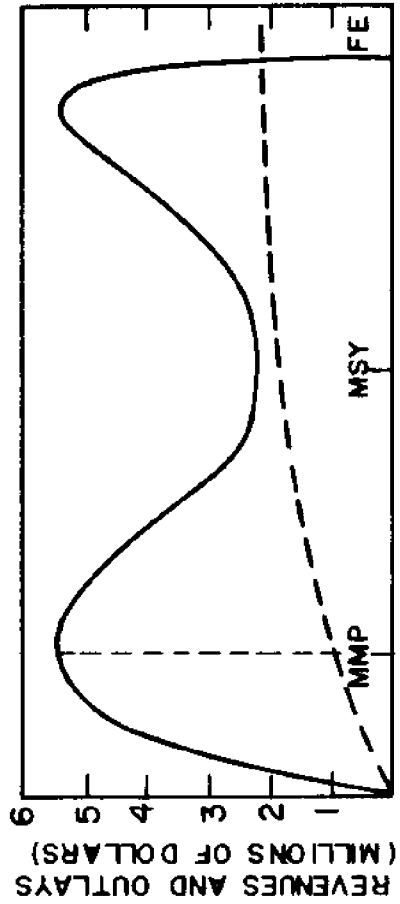


Figure 2.2.3 Fisherman revenues and outlays.

Yield, an increase in landings can actually decrease fisherman revenues. In this case we will have a local minimum in revenues in the region surrounding the MSY point as shown.

The revenue curve can be double-humped.* There is a wide range of combinations of yield-efforts and price-landings relationships for which this is the case. This double hump has some very important implications for fisherman versus fish purchaser income, as we shall see.

The dotted line in Figure 2.2.3 is a hypothetical long-run fisherman cost curve, total fisherman outlays as a function of fishing effort. This cost is assumed to be defined in present-value terms and thus to fully include normal return to capital employed in this fishery. The difference between total revenue and total cost so defined represents the excess profits of the fishing fleet, that is, profits above the normal return to capital. Since some people will object to the adjective "excess" and since some of the "profits" will, given the lay system, actually be transferred to the fishermen themselves in the form of earnings above what they could obtain in alternative employment, we will relabel this difference the fisherman surplus. This difference as a function of effort has been plotted in Figure 2.2.4. Like total revenues, it too can be double-humped. However, these humps will be less symmetric than the revenue humps due to the difference in fisherman outlays between the right and left humps. The peak of the

*To our knowledge, this was first pointed out by Anderson [1973].

**This asymmetry can be increased by differences in quality. At the right-hand hump, the individual landed fish will be larger than at the left-hand hump, due to the older population distribution. In many fisheries, larger fish command a higher unit price.

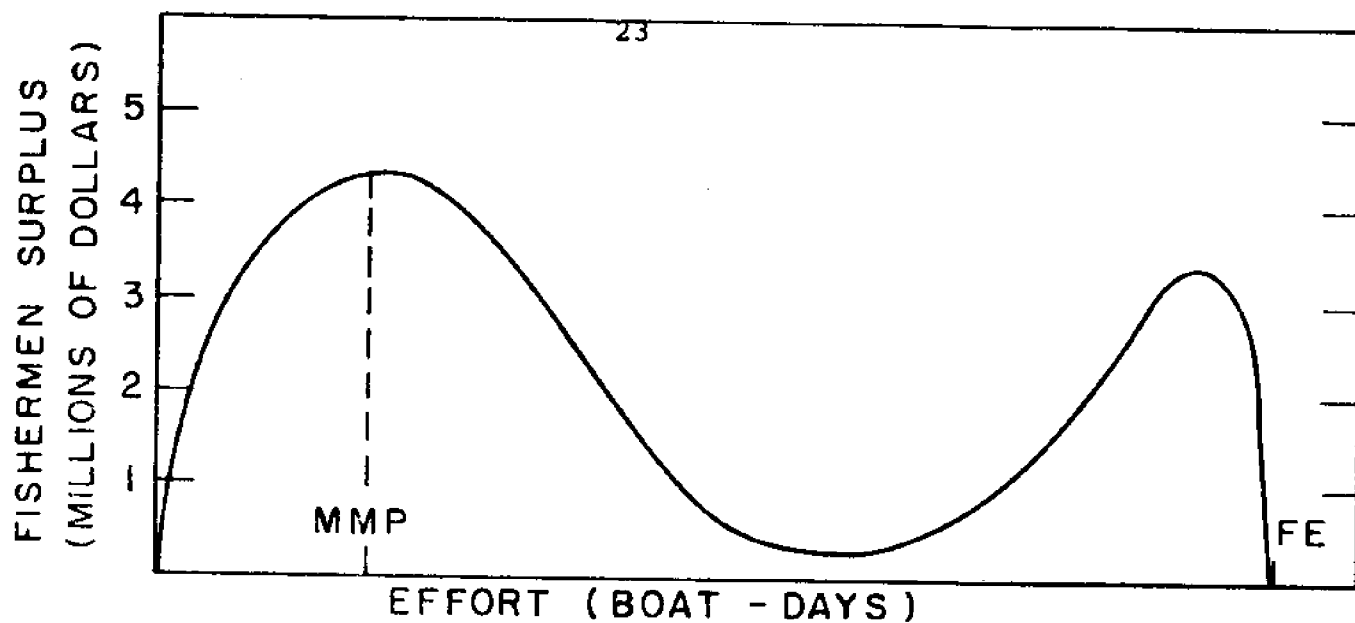


Figure 2.2.4--Fisherman surplus vs. fishing effort.

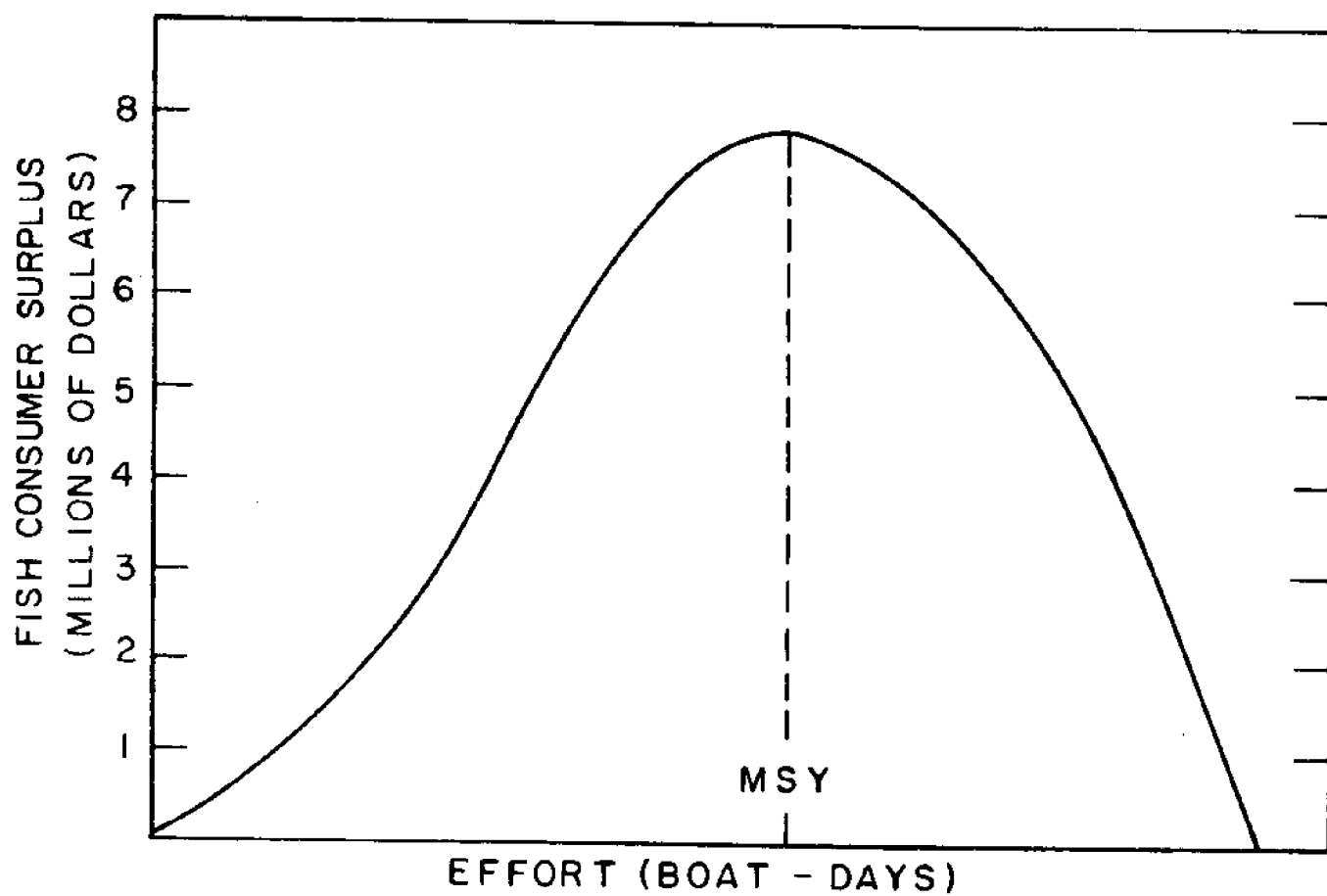


Figure 2.3.1--Consumer surplus vs. fishing effort.

leftmost hump we shall call the maximum monopoly profit (MMP) level of effort. If the fishery were owned by a single, selfish individual, who had complete control over its management and who wished to maximize his own income, this is the point at which he would operate. On Figure 2.2.3, it is the left-most point where the slope of the revenue curve equals the slope of the cost curve.* Thus, it's always to the left of the Maximum Sustainable Yield point.

Another point of interest is that on the right-hand side of Figure 2.2.4, marked FE for Free Entry. To the left of this point, the fishing fleet as a whole has a positive surplus, that is, it is making money above and beyond the normal return on capital; to the right of this point, the fleet as a whole is suffering losses. In the absence of absolutely any controls on entry, the level of fishing effort will tend to FE. If fishing effort is less than this amount, the boats and labor will be earning more than they could elsewhere and more boats and people will enter the fleet in an attempt to share this profit. If fishing effort is greater than this amount, the fleet as a whole will be losing money, and the weakest boats will be forced out of the fishery. FE is, then the equilibrium effort and yield under free entry.

As shown, this 'equilibrium' can be quite unstable. Levels of effort slightly above the Free Entry point will generate sharp drops in yields, eventually forcing all but the

*In the fisheries economics literature, this point is often misleadingly called the Maximum Economic Efficiency (MEE) level of effort. This nomenclature is a result of fishery economists' persistent refusal to include fish consumer income in their thinking. Notable exceptions include Anderson [1973] and Gates [1974].

most efficient operators into bankruptcy and off the resource. Assuming the resource is not completely wiped out, after a time, it will recover, the remaining operators will begin generating a positive surplus which in turn will attract new capital and the process will repeat itself. Given the dynamic response of fisheries to overfishing, the Free Entry point can easily be a very transitory equilibrium indeed. Nonetheless, it is a useful concept as long as we remember its limitations.

2.3 Fish consumer income

Fishermen are not the only group in whose income we are interested. If we wish to manage the resource in such a manner as to maximize national wealth, we must also consider the fisherman's customers, for after all they are Americans too. With any particular level of effort e , there will be a corresponding yield $y(e)$, and price $p(y(e))$ as shown in Figure 2.3.2. If effort is very low, the yield will be low and the price high. Consumers will be consuming very little fish and paying a high price. If the level of effort is very high, the yield will be low, price high and once again the consumer will be eating very little fish at a high unit price. At intermediate levels of effort more fish will be landed (and consumed) and the price will be lower. Obviously, consumers' real income will be higher in the latter situation than in the first two. Not only will fish eaters be able to consume more fish but they will do so at a lower price. An approximate

measure of the aggregate difference in consumer real income associated with changing from a low yield situation $y_L(e_L)$ to a higher yield situation $y_H(e_H)$ is the area under the demand curve between the price in the high yield and the price in the low yield situation. Very roughly speaking, this area is the difference in price time the amount consumed. More precisely,

$$\int_0^{y_H(e_H)} p(y(e))y(e)dy(e) - p_H(y_H(e_H))y_H(e_H) \\ - \int_0^{y_L(e_L)} p(y(e))y(e)dy(e) - p_L(y_L(e_L))y_L(e_L)$$

The first term is the difference between what consumers as a whole would be willing to pay, if they had to, and what they will actually pay for the amount of fish landed in the high yield situation. The second term is the similar quantity for the low yield situation. The first term measures how much better off the fish consumers are in the high yield situation in real income terms over what they would be in a no yield situation. The second term measures how much better off the consumers are in the low yield situation over a situation in which no fish are landed. The difference in these differences then is the change in consumer real income associated with moving from a low yield situation to a higher yield situation, summed over all consumers. In terms of Figure 2.3.2 it is the hatched area under the demand curve between the lower and

higher prices.

If we are analyzing more than two fishery management alternatives, we will in general have more than two price-landing points which we must consider. In this situation, we must specify a baseline yield point against which all changes in fish consumer income can be compared on a systematic basis. The specification of this baseline yield is arbitrary. One obvious candidate is the zero yield level, point z on the demand curve. The increase in real aggregate consumer income associated with any positive yield, Y , and its corresponding price $p(Y)$ relative to zero yield is the area under the demand curve to the southeast of $(Y, p(Y))$. This area is known as the consumer surplus $CS(Y)$ associated with Y .

$$CS(Y) = \int_0^Y p(y) \cdot y dy - p(Y)Y$$

While the zero yield point is an obvious baseline against which to measure changes in consumer income with changes in landings, it does have one practical disadvantage. It requires that we know, or at least be able to approximate, the demand curve over the entire range from maximum yield down to no yield at all. In some fisheries, where we have experienced zero or near zero yields this may not be a problem. However, in many cases, we will be interested in, and have empirical data over, a much narrower range of yields running, say, from Maximum Sustainable Yield to Free Entry Yield. In such situations, a more workable baseline may be the status quo or the Free Entry level (which may be the same). The point is that it doesn't really matter. Since we are only interested in

changes in consumer real income with changes in yield and price, we can relate these changes to whatever baseline we find easiest to use. Of course, once we've chosen a baseline yield and price, we must maintain this same baseline throughout the analysis.

In Figure 2.3.1 we have chosen zero yield as the baseline.

Figure 2.3.1 shows the consumers' surplus associated with the yield curve of Figure 2.2.1 and the hypothetical demand curve of Figure 2.2.2 expressed as a function of level of effort. Notice that in contrast to the fishermen's surplus curve the consumers' surplus curve is sharply peaked in the neighborhood of the MSY point and in fact the yield maximum and the consumers' surplus maximum occur at the same level of effort. Also, there is a roughly anti-symmetric relationship between the consumers' surplus curve and the fishermen's surplus curve. Clearly, we have a conflict between fish supplier income and fish consumer income. Fish suppliers will maximize their income at the MMP point where the slope of the revenue curve and outlay curve is equal, while consumer income will be maximized at the MSY level. If either the slope of the cost curve is high or demand is inelastic, the level of effort which maximizes fishermen income and that which maximizes consumer income can be quite different. Moreover, as shown, the differences in fishermen and consumer wealth associated with the differing philosophies toward management can be very large indeed.

2.4 National income and the total pie

One way of resolving this conflict is to ask what level

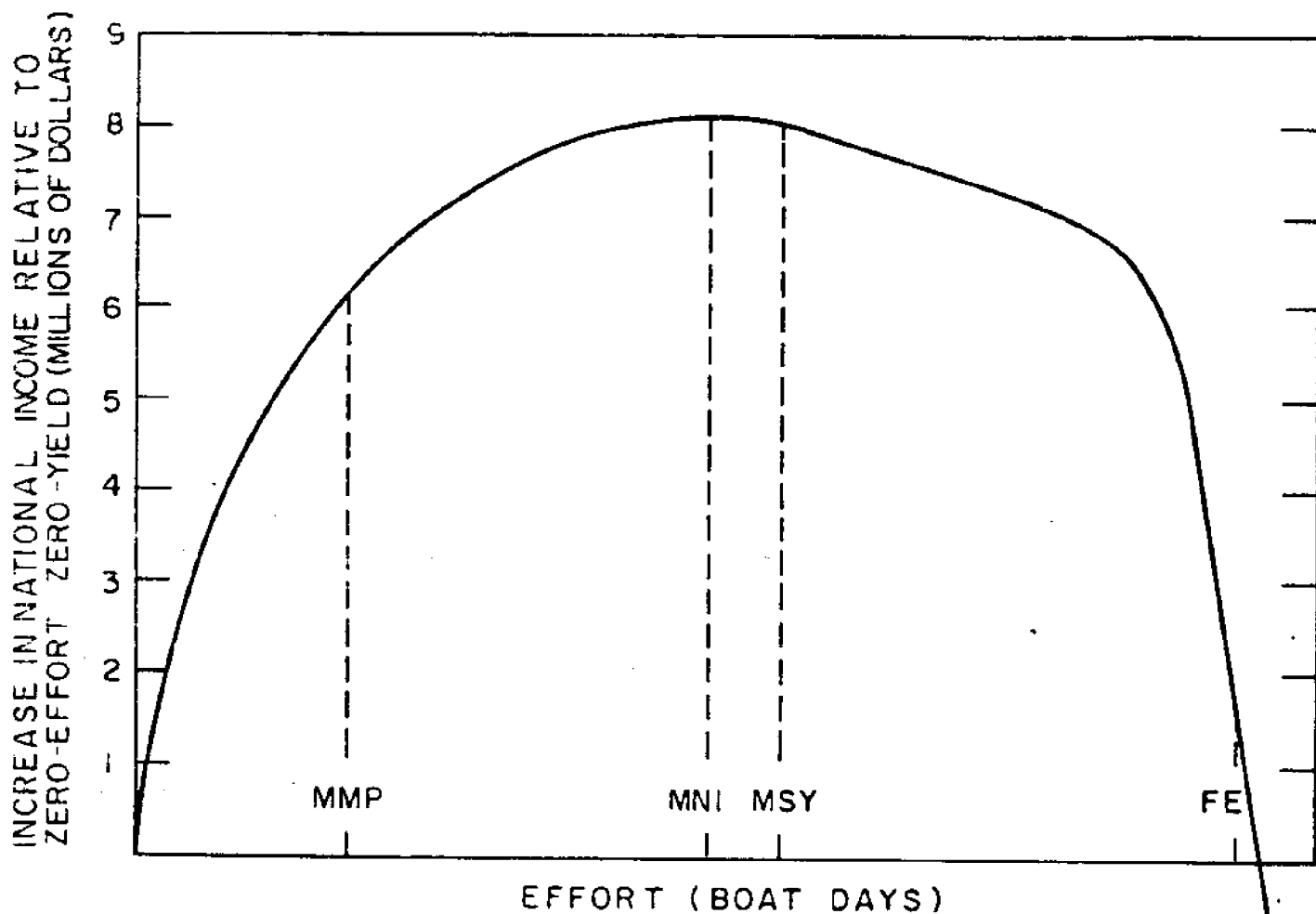


Figure 2.4.1--Sum of fishermen and fish consumers' surplus--total increase in national income relative to zero effort-zero yield.

of effort maximizes the sum of fisherman income and fish consumer income; that is, what level of effort maximizes national income. In asking ourselves this question we are focusing on the overall size of the pie rather than on the individual pieces. Figure 2.4.1 plots this sum as a function of effort for the yield curve, demand curve, and cost curve of Figures 2.2.1, 2.2.2, and 2.2.3. Figure 2.4.1 is merely the sum of Figures 2.2.4 and 2.3.1. The first thing we notice is that the overall size of the pie is very definitely not fixed. By drastically overfishing or underfishing the resource, everybody loses. The level of effort at which the sum of fishermen surplus and consumer surplus is maximized we will call the MNI (Maximum National Income) point. This point will fall between the MMP level (maximum fishermen surplus) and the MSY level (maximum consumers' surplus). It will in fact be the point where the slope of the cost curve equals the market price. One way of obtaining insight on this point is to imagine that the fishery is divided up into a large number of 'fishsteads'. Each individual fisherman has complete control over the stock on his fishstead. His stock is somehow confined to his fishstead and no one else can fish it. Then in deciding how much of his stock to harvest each year, each fishsteader, in attempting to maximize his own profits, would compare the market price with the additional cost to him of his producing his most expensive unit, and harvest up to the level where the market price equals this marginal cost. In this situation, the aggregate level of effort would tend to the MNI point. Each fishsteader operating

individually would, unlike a single monopoly owner of the entire resource, regard the market price as fixed or at least out of his control. Thus, he would not restrict output simply to raise price. On the other hand, he would be induced to cultivate and husband his stock in a manner to maximize his long-term profits at the given market price, for he need not fear that someone else will harvest the stock that he is husbanding. This divvying up the resource and assigning private property rights to each segment is, of course, the solution that society came up with on land for exactly the same resource management problem we now face in fisheries.* Unfortunately, establishing and enforcing private property rights to portions of a fishery is currently infeasible, or to put it more precisely, is for most--not all--fisheries extremely expensive.** Therefore, if we are to manage a fishery in such a manner as to maximize national income we will have to come up with management schemes which simulate the solution obtained on land by assigning private property rights to a large number of people and fostering (or at least not completely interfering with) competition among the numerous suppliers so created.

*See Hardin, "The Tragedy of the Commons," in G. deBell, The Environmental Handbook, Ballantine Books, 1970, New York.

**This need not always remain the case. The same thing was true of Western ranch land until the invention of barbed wire--probably one of the most underrated inventions of all time. The technical solution to the fishery management problem would be for someone to invent an oceanic barbed wire. We could then sell off the grounds, disband the Regional Councils and NMFS, and leave the management problem to the market.

There is one more insight we can garner from our simple yield-effort, price-landings analysis. In one sense, our concentration on the conflict between the level of effort which maximizes fisherman income and that which maximizes consumer real income is completely misplaced. As we have seen, under Free Entry, the yield will tend neither to the MMP nor MSY levels nor anywhere inbetween but rather to the Free Entry point which may be far to the right of either. At this point yield is low and fisherman costs are high. Fisherman are barely breaking even and consumers are obtaining an unnecessarily low quantity of fish at high price. Everybody is losing. Both fisherman and fish consumer income are lower than they need be, possibly much lower. National income is doubly strained by both low yield and the large amount of resources (men, vessels, and fuel) devoted to obtaining this low yield. In such a situation, it may be the case that both sides would gain by an agreement to move to any point between MMP and MSY. One can easily postulate situations where not only will national income, the overall size of the pie, be increased by such a decrease in effort but the real income of both fishermen and consumers increased as well.

However, it is important to point out a very major stumbling block that may be in the way of such an agreement. And That is the rightmost hump in Figure 2.2.4. Suppose, just suppose, that we do not have completely free entry to a particular fishery. Even with no regulation, there may be a number of subtle and not-so-subtle limitations to entry: lack of dock

space and imperfect markets in dock space; familial and cultural nepotism in crew selection, careful husbanding of monopolies on fishery knowledge and experience, successfully hiding the fact that surpluses are being earned. Suppose that under the influence of such barriers to entry, fishing effort had stabilized at slightly below the Free Entry level, that is, in the vicinity of the right hump in Figure 2.2.4. The fishermen, if nobody else, know they're doing pretty well. True, the situation is precariously unstable, easily upset by natural fluctuations in population, improvements in fishing technology, or new entrants. But it is the status quo. If such a situation exists, then it may be extremely difficult to get the fishermen to agree to the wholesale decrease in fishing effort required to adjust down to below the MSY point. For one thing, there are many points between the MMP level and the MSY point where fishermen income is less than it is in the vicinity of the right hump. Fishermen as a whole would be taking a big chance in moving from the known benefits of the rightmost hump to the unknown world of the leftmost hump and some fishermen would have to leave this profitable industry entirely with a certain loss in their individual income unless explicitly compensated.

Even if fishing effort has stabilized at the Free Entry point where the fishermen are barely breaking even, the rightmost hump still presents a very substantial barrier to reform. It is in the nature of reforms made in the political arena

that it is easiest to move incrementally. In the case at hand, this would involve gradual reduction in the fishing effort as the fleet naturally attrits under old age, etc. This might work as long as the fishermen noted that with each reduction in fishing effort, fishermen income improved. This would be the case while the fleet was moving from the Free Entry point to the peak of the right hump. However, from that point on each further reduction in fishing effort would result in a decrease in fishermen income as the increased yields dropped the market price. This decrease in fishermen income could be quite substantial and would continue until fishing effort dropped below the MSY point. Long before that happened we could be sure that the fishermen would be screaming bloody murder. In summary, the rightmost hump in Figure 2.2.4 may not only explain why so many fisheries have been able to maintain a relatively stable, although grossly overfished, condition but also presents the real world implementation of any effective resource management system with a very sizable political barrier. If the combination of yield curve and demand curve is such that a right hump exists, an incremental approach to reducing effort almost certainly will not work.

2.6 The need for management

From the point of view of near-term American fishery policy, perhaps the single most important feature of this chapter is that nowhere in this discussion of fishery management problems does the word 'foreigner' appear. It was not

necessary to postulate foreign fishing effort to generate gross overfishing. We required only Free Entry for domestic fishermen. The basic problem is not the foreigner but the fact that no individual can obtain property rights to a portion of the fishery allowing him to cultivate and husband his stock.

If we throw the foreigners out, we would still have to come to grips with this basic problem for the domestic fishermen's surplus so generated will simply attract more domestic capital and men until we have reapproached the Free Entry level of effort and the profits disappear. The central issue is not the foreigner, its Free Entry to a resource over which private property rights cannot be enforced. Indeed McHugh has argued persuasively that the actual history of the management of the international fisheries, poor though it is, is better than the history of management of the purely domestic fisheries such as the soft clam, the hard clam, and the oyster [McHugh, 1972]. Even if domestic fishing had to expand to regenerate the Free Entry level of effort, we can be sure that drawn by the momentary surplus associated with the expulsion of the foreigners, it would. And for most species, as we have seen, they may not have to expand very far. In short, whether or not foreigners are present, both foreign and domestic effort must be managed by a third party if we are to avoid a grievously overexploited situation and possibly the loss of the resource.

This raises the question of how the resource should be managed. In order to obtain insight on this issue, the MIT Sea Grant Program has developed a bioeconomic model of a fishery,

which we have dubbed FISHDYN1. FISHDYN1 has been tested rather extensively on the Georges Bank yellowtail fishery. The remainder of this report describes this model and the results of these tests.

CHAPTER 3

GENERAL DESCRIPTION OF THE
MIT SINGLE-SPECIES FISHERY SIMULATOR, FISHDYN3.1 Basic premises

The model which has been developed to analyze some of the issues raised in Chapters 1 and 2, FISHDYN1, is based on five fundamental premises:

1. exogenous control;
2. single species;
3. dynamic rather than steady-state with the ability to handle recruitment over-fishing as well as growth overfishing;
4. explicit incorporation of our uncertainties about the critically important stock-recruitment relation;
5. inclusion of fish consumer as well as fish supplier income.

3.1.1 Exogenous control

By exogenous control, we mean that the analysis assumes that the managers of the resource--whoever they might be--have complete and unfettered control over the exploitation of the stock. They can impose catch restrictions, gear restrictions, effort restrictions through time in any manner whatsoever and enforce these restrictions. They have control over new capital investment in the fisheries, the amount of effort devoted to each species, and exercise this control. In terms of the New England situation, we will act as if Georges Bank Inc., an efficient, public-spirited organization interested in maximizing the present-value national income obtainable from the resource, owns and operates the fishery. From the point of view of the programming,

this implies that all the fishing effort variables (number of boats of each size and type category, quotas, mesh, trip length, effort on each fishery, etc.) are specified by the users of the program. The model does not attempt to internally simulate the responses of individual fishermen to the actual freedom they may have in choosing when and where to fish, how much and what type of new equipment to invest in, etc. Rather, the model assumes the individual fisherman or fishery investor has no such freedom.

In reality, of course, there is no such thing as Georges Bank Inc. Rather, there are several hundred individual entities exploiting the Bank, each trying to maximize its own income. These entities are under the loose, untested control of the Regional Council. The Regional Council has no direct power over investment or individual application of effort and has limited enforcement rights. Pragmatically, the Regional Council's control may be limited to overall quotas and perhaps licensing arrangements which will prevent new entrants into the fishery but do nothing with respect to the current excess domestic fishermen. To make matters worse, the Regional Council itself is made up mainly of members who have a direct or indirect interest of long standing in the regional fishing industry. It is not clear that these individuals will impose harsh measures on their colleagues in the industry.* Fish

*It is also far from obvious that they won't. The Northwest Council has acted decisively in attempting to close down the salmon trawl fishery when it became clear that escapement goals were not being met.

consumer interests have only token representation. One may be forgiven for suspecting that if the Regional Councils function effectively, it will be toward the goal of maximizing fisherman income and not national income.

Why, then, a model which assumes away all these political, legal realities? Our purpose is not to simulate what is likely to happen.* Our purpose, rather, is to demonstrate what could be and how it could be accomplished. Our hope is that such demonstration will place at least some pressure on the body politic to improve the political, legal realities.

3.3 Single-species

FISHDYN1 is a single-species model. That is, interspecies interactions are not simulated explicitly. This important limitation was accepted on the following grounds.

1. Available diet data indicates that, at least for some of the more important Georges Bank species--including yellowtail, the focus of our effort at this time--the interspecies relationships may be rather weak.
2. A first-things-first attitude. It is our belief that before moving to multi-species models, we should push single-species models as far as we can. In particular, we feel that it is critically important to incorporate the stock-recruitment feedback and

*Actually, the structure of the programming is such that it would not be very difficult to allow at least some of the fishery control variables (for example, new investment) to be endogenously determined.

our uncertainty about this relationship into dynamic fisheries models.

The principal swimming species of economic value to American fishermen on Georges Bank are: (1) cod; (2) haddock; (3) yellowtail flounder; (4) other flounder (winter flounder, witch, American plaice, and fourspot flounder); and (5) herring.* Our basic approach is to analyze each of these species, one at a time. That is, in analyzing each species, the model ignores interspecies interactions. On the biological side (predation, competition for food), available diet evidence indicates that these interactions may be rather weak. Haddock and flounder feed almost exclusively on bottom-dwelling worms, starfish, and crustacea [Wigley, 1956]. Only 2.4% of haddock diet, .8% of yellowtail diet, and 6.6% of other flounder diet is fish. Wigley and McIntyre [1964] report that there is plenty of bottom-dwelling fauna on the Bank to support these species at their MSY and better. Further, the haddock and flounder species are geographically separated by water depth, water temperature, and bottom type preferences [Bigelow and Schroeder, 1953].

The herring is a midwater fish which feeds on plankton. The only possible interaction between this species and the bottom-dwelling species listed above is herring predation on demersal species larvae. But examination of herring feeding

*Mackerel has been left out because its migrating pattern takes it well outside the 200-mile limit, thereby generating a unique set of management problems. Other Bank species of somewhat less importance which could and should be analyzed in a similar manner are hake, redfish, and pollock.

habits has revealed no such dependencies. Herring appear to feed almost exclusively on minute worms (chaetognaths), shrimp (euphausiids), and mollusks (pteropods) [Maurer, 1976].

The only real adult predator interaction involves the cod: the cod is a considerably larger fish than the others and is known to prey on all the other species. However, the apparent proportions for the most part are small. Maurer [1975] reports that yellowtail constitute 2.5% of the diet of cod, and other flounder 1.5%. Haddock percentage was less than .5%, but then there haven't been many haddock around. Fifteen percent of the diet of cod on the Bank is herring, by far the strongest interspecies prey relationship reported for the species under analysis.* Young cod (5-20 centimeters) can be a very important component of cod diets [Maurer, 1975a]. But, of course, single-species models are quite capable of describing cannibalism.

In summary, with the possible exception of the herring-cod interaction, the biological prey-predator relationships between the species being analyzed appear to be of secondary importance and will be ignored.

*Cod diets in the Gulf of Maine of 27% herring have been observed [Maurer, 1975a].

The by-catch question is not so easily begged. Even if the effort is directed as desired, some by-catch will necessarily be generated. Table 3.3.1 shows estimates of current by-catch rates (tons of by-catch/ton of target catch) in the Georges Bank fishery [Palmer, 1976]. In all our species except cod and haddock, the by-catch appears to be a relatively minor problem. As might be expected, the by-catch of demersal species associated with herring fishing is nil. Fishing directed to flounder apparently catches relatively small amounts of cod and haddock (.03 tons cod/ton flounder and .06 tons haddock/ton flounder), although there has been no breakdown of the yellowtail/other flounder relationships and all haddock figures must be viewed with caution due to present extremely depleted condition of the haddock stock.

The big problem once again is clearly the cod. Cod is a relatively wide-ranging, omnivorous fish less tied to particular depths and particular bottom types than the other species. Hence, cod fishing generates relatively large by-catches, particularly of haddock. An obvious next step in the analysis is a combined cod/haddock and possibly a yellowtail/other flounder model.* However, this was not done due to resource limitations.

*The present programming is designed to facilitate later extensions to multi-species.

TABLE 3.3.1
BYCATCH RATIOS

Species Sought	Species Caught				
	Cod	Haddock	Yellowtail	Other Flounder	Herring Mackerel
Cod	1.00	.10	.02	.06	.00+ .00+
Haddock	.33	1.00	.03	.02	.00 .00+
Yellowtail	.09	.01	1.00	.09	.00 .00
Other Flounder	.40	.07	.39	1.00	.00+ .00+
Herring	.00+	.00	.00+	.00	1.00 .07
Mackerel	.00+	.00+	.00+	.00+	.09 1.00

Source: Palmer, Brown, and Brennan [1976], p. 8. Rates for 1972 through 1974 averaged.

Perhaps the single most important reason for our decision to concentrate on one species at a time is our belief that there are other phenomena which we must incorporate in our analysis before moving to multi-species analysis. These phenomena are discussed in the next three sections.

3.4 A dynamic model rather than steady-state

The easiest decision we had to make in model formulation was the choice between a dynamic model which attempts to follow the transients associated with non-equilibrium populations, non-equilibrium level of fishing, and both fishing- and naturally-induced fluctuations in recruitment, rather than a model which attempts to generate the steady-state (equilibrium) situation associated with a postulated level of fishing. As we have seen in Chapter 2, it is possible to obtain some valuable insights from steady-state analysis.* However, there is considerable difference between insight and a concrete management plan. Moreover, steady-state analysis ignores some critically important phenomena.

*Chapter 2 should most certainly not be regarded as an exhaustive exploitation of steady-state analysis. For a much more representative example of what can be learned from equilibrium reasoning, see Gates and Norton [1974].

Currently, none of the Georges Bank fisheries are in anything approaching an equilibrium state. This can be readily seen from recent deterioration in catches, wholesale adjustments of foreign fishing efforts both before and as a result of the 200-mile limit, and the steep reductions in ICNAF quota recommendations. Therefore, even if we believed in a stable steady state, we would be faced with the management problem of how do we get there. In so doing, the most important information we have is the current, non-equilibrium age distribution of the population and current estimates of next year's recruitment, whether these estimates be based on the population distribution or actual trawl surveys. To throw away this data would be foolhardy in the extreme.

Much more basically, there is little evidence that a stable steady state for these stocks even exists and considerable evidence that it does not. In almost every fishery that has been documented for a substantial length of time (several decades or more) large-scale fluctuations in population have been noted. In many cases these fluctuations have occurred before fishing mortality could have been an important factor. Various attempts have been made to relate these fluctuations to natural fluctuations in water temperature, currents, plankton blooms, etc., with indifferent success. But it's clear the natural fluctuations are there and that they're extremely important. It also seems clear that these fluctuations operate through the egg and larval stages rather than adult mortality and growth [Cushing, 1977].

These stabilizing mechanisms, such as density-dependent competition for food among the larvae and cannibalism by older fish of the same species,* can be rather weak and, most importantly, they operate with a significant lag. The regulation of larval and juvenile mortality is not fully reflected in the adult stock for a period of at least a year and, in some cases, for three or four years.

Whenever an engineer is confronted with a dynamic system, the first thing he asks himself is: What are the lags? What are the delays between the time the system is perturbed and the time the restoring force becomes active? For he knows that these lag times will be crucial in determining whether a system will quickly damp out any perturbation, or will continually fluctuate at some natural frequency, or will become unstable and collapse. While the crucial importance of lags in the response of dynamic systems has been well known in physical systems for a century or so, it wasn't until the last twenty years that economists and managers became aware that lags play an equally important role in economic and social systems.

Our reading of the fishery literature would indicate that fishery management, for the most part, is still based on equilibrium models. Equilibrium reasoning and equilibrium models are useful only if the system is near equilibrium and that equilibrium is stable with respect to likely perturbations which may be placed on it. We will argue that, at least with respect to the Georges Bank yellowtail, neither of these conditions is even approximately met. Recent work done by

*Cannibalism can be both stabilizing and unstabilizing, depending on one's assumptions about the form of cannibalism and the momentary size of the adult (or predator) and juvenile (prey) stocks.

Lett and Doubleday and their colleagues at the Atlantic Biological Station (ABS) in Halifax has led to the same conclusion with respect to a number of other species [Lett, 1975, Lett, 1976, Doubleday, 1976]. This group has constructed models of the St. Lawrence cod, mackerel, and herring incorporating both the lag in stock-recruitment relationships and random perturbation in recruitment. These results indicate that even without any fishing, the system is barely stable. The natural frequencies without fishing mortality appear to be of the order of five (mackerel) to twenty years (cod). The amplitude of the fluctuations in total base from peak to trough for cod is approximately 100% of the mean biomass. The amplitude of the natural fluctuation in the pelagics is still higher. In short, no strongly stable steady state appears to exist for these systems. We will obtain evidence that yellowtail is susceptible to the same sort of lightly damped, stock-recruitment driven fluctuations.

The ABS group also makes the extremely important observation that different management alternatives--sometimes regarded as equivalent--will have drastically different effects on such a fluctuating system. For what should be an obvious example, limitations on effort tend to be stabilizing while quotas tend to be destabilizing. In the first case, the catch tends to vary with the biomass; in the second case, a smaller proportion of the biomass is caught when biomass is high--a time when the proportion of the fish caught should be increased--and a higher proportion of the biomass is caught when the biomass is low--a time when the proportion of fish caught should be

In any event, given biological systems which at best are weakly stable, any model which does not capture the lags in response of the systems to a perturbation, whether it be natural or manmade, fails to address the crux of the matter and will yield completely unreliable results. Steady-state analysis ignores these lags and hence in our opinion cannot be used for managing such a system.

3.5 Explicit incorporation of uncertainty within the model

Fishery biologists are continually bemoaning their lack of knowledge of the subject about which they are the experts. There's sometimes an element of self-serving sales talk in this position, but for the most part this feeling is based on honest professional conservatism regarding our knowledge concerning an extremely hard to observe, hard to control set of phenomena. However, professional modesty is one thing; using one's lack of complete knowledge as an excuse for avoiding management responsibilities is quite another. The fact is we know quite a bit about fisheries and the Georges Bank fisheries in particular. There are other things we don't know now which presumably someday we will know, such as a better description of the stock-recruitment relationships. There are still other things we will never know with certainty--such as what will be the hydrographic conditions on the Bank during next year's spawning seasons. A portion of our present uncertainty is caused by nature and will always be with us. A portion of our present uncertainty

is caused by our own ignorance and will be at least partially corrected in the future. But the Bank must be and will be managed now. The only question is whether we will manage it to the best of our ability given current uncertainties or not.

The obvious importance of our uncertainties is not an argument for ducking responsibility; rather, it's an argument for incorporating these uncertainties explicitly in our analysis. This argument becomes overwhelming when we realize that we have at best a weakly stable, lightly damped system whose collapse is well within our power. There is no need to detail the usual litany here--the Baltic herring, the Downs herring, the Georges Bank haddock, the Pacific sardine, etc. With a system which is so sensitive to external perturbations, whether they be natural or man-made, ignoring uncertainty in our analysis makes as much sense as analyzing the Gambler's Ruin problem as if we knew which numbers were going to come up on the roulette wheel.

Perhaps the one really original element in FISHDYN1's makeup is its treatment of this uncertainty with respect to stock-recruitment. FISHDYN1 has three basic stock-recruitment modes:

A. Recruitment is independent of adult biomass and is exogenously specified by the user through time. Under this assumption, FISHDYN1 becomes a conventional growth over-fishing model. If effort is held constant, the model will after a time go to steady-state.

B. Deterministic, Ricker-form recruitment. In this mode, the model uses a Ricker stock-recruitment curve. Our approach to obtaining the parameters of this curve has been to apply Bayesian regression to a scatter diagram of past recruitment versus adult biomass, suitably lagged, obtaining the maximum likelihood estimates of the required parameters.

C. Monte Carlo sampling of a set of recruitment densities. The result of Bayesian regression of past stock-recruitment data is not only the maximum likelihood estimates of the parameters of the Ricker form but also a set of recruitment densities conditioned on current biomass. In Recruitment Mode C, these densities are transmitted to FISHDYN, which then samples from them in the course of its simulations. In Mode C, recruitment is random, reflecting our uncertainty about this variable. In this mode, it is necessary to run the simulation over and over again to generate meaningful statistics about the possible future of a particular fishery under a particular level of effort. In return for this added effort we have a model which does incorporate our uncertainty about stock recruitment at the heart of its simulation. A goodly part of Chapter 4 is devoted to discussing how this is done. Programming for automating the entire process from raw stock-recruitment data to output statistics has been developed.

3.6 Inclusion of fish consumer as well as fish supplier income

If there is a theme to Chapter 2, it is that the fish consumer has a stake in fishery management which can be as large as that of the fisherman. Implicit in the chapter was the idea that the concern of public management of a public resource is properly the public as a whole rather than only the welfare of the group exploiting the public resource. This is, to be sure, a naive idea which has rarely been acted upon in the management of other public resources and very possibly not in the management of the Georges Bank fishery as well. Nonetheless, we will persist. We will assume the ultimate objective of fishery management is increasing national income--the total size of the pie--rather than anybody's share. This implies that our model must both simulate price fluctuation associated with variation in landings and compute the changes in consumer income associated with these fluctuations. Thus, the model will output its estimate of the effect of a postulated management scheme not only on fisherman income, but on fish consumer income as well, and the sum of the changes in fisherman in fish consumer income--the effect on national income. In a sense, FISHDYN1 is neutral on the fisherman versus fish purchaser issue. The model computes the present value of the fisherman's surplus, the present value of the fish consumer's surplus, and the present value of the sum of these surpluses for each of the fishery

management policies it is asked to investigate.* Therefore, whatever one's objective function, the results will be of interest.

*When the model is operating in the Monte Carlo recruitment mode, it prints the sample mean and the sample variance of each of these economic quantities.

CHAPTER 4

DESCRIPTION OF THE MODEL PROPER

4.1 Overview and input format

The programming implementing FISHDYN1 is organized as shown in Figure 4.1.1. The model comprises a main program, DRIVER, and three subroutines: CATCH, MARKET, and RECRUIT. The model is designed to be used interactively. DRIVER reads in input data from the user's terminal, refers to user-selected files on disk for further input data, calls the subroutines as required in the course of the simulation, and at the end of each simulated year, prints a summary of the results back to the user's terminal. Internally, the model operates on a monthly interval. That is, each month in simulated time, DRIVER refers to the CATCH subroutine which uses the current population distribution and the current applied effort by vessel category to estimate the catch by age for that month. Then DRIVER refers to the MARKET routine which estimates the monthly price which is consistent with the level of landings generated by CATCH. At the end of each year, DRIVER ages the population and refers to RECRUIT, which estimates future recruitment according to Mode A, B, or C, depending on the user's specifications.

As Figure 4.1.1 indicates, input data is drawn from two sources:

1. directly from the user's terminal interactively;

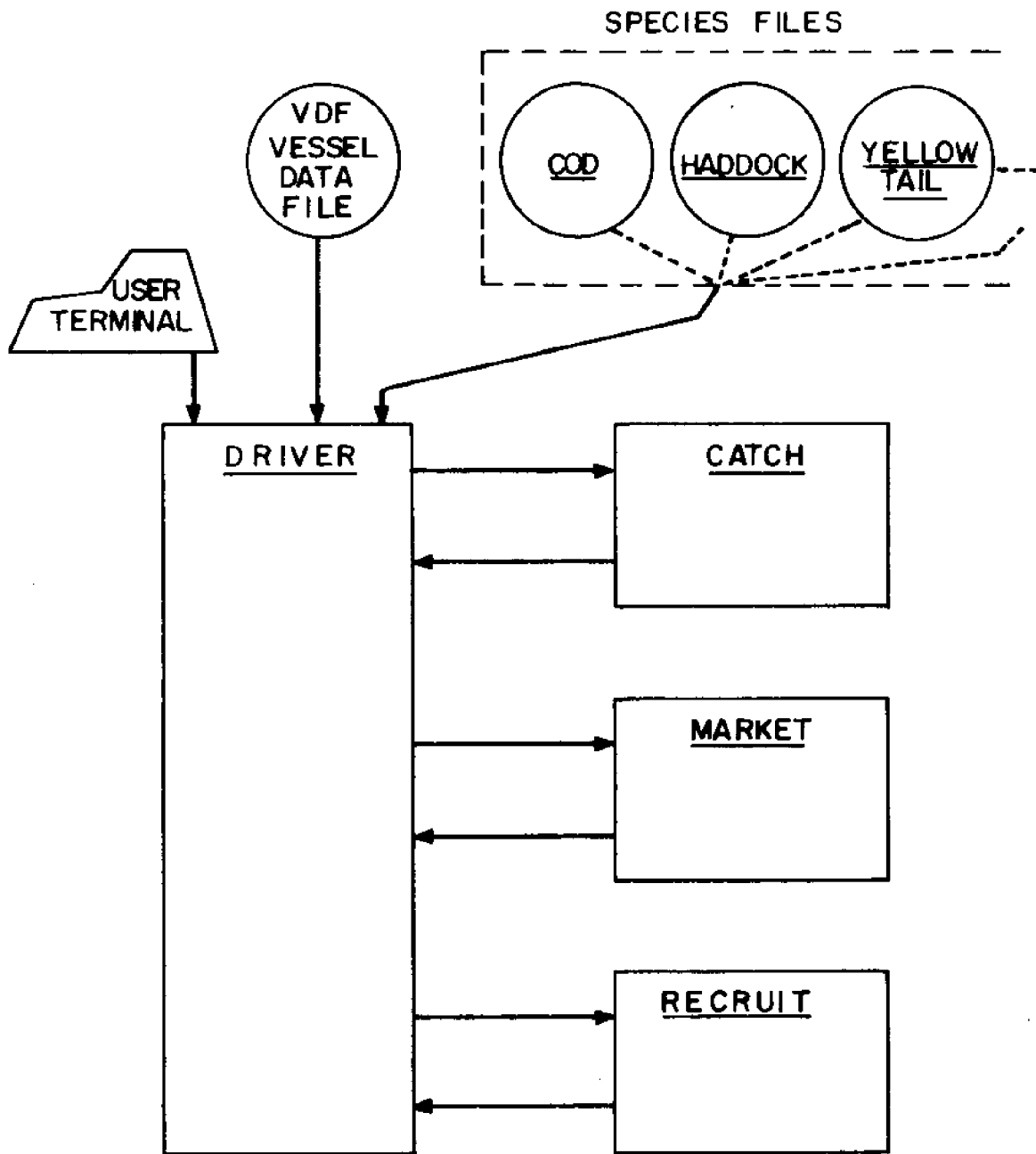


FIGURE 4.1.1 FISHDYN OVERALL ORGANIZATION

2. from user-selected files stored on disk.

Table 4l.1 shows the input portion of a typical run. The program first prompts for a title whose only purpose is to identify the subsequent output. The model then asks which species is to be simulated in this run. The user's response identifies one of the species files on disk which is thereupon read into core memory.

Each such species file has the form shown in Table 4.1.2. The first nine lines are documentary prose which is ignored by the model. The tenth line contains the species name, age at recruitment, maximum age, followed by minimum exploited age as a function of mesh size. Six different mesh sizes are allowed. Currently, the model assumes knife-edge recruitment at the user-selected mesh size. The default is no mesh-size limitation.

The next five lines contain age-dependent data for the species. The first such line merely identifies the age columns. The second contains natural mortality rate (percent per year) as a function of age. The third line contains the initial population distribution in millions of fish for each year class. The next line contains weight at age in grams. The following line contains length at age in centimeters. Currently, the model makes no direct use of this particular vector and it may be left blank if desired.

The last line in the age-dependent section contains an age price-premium factor. At each monthly increment, the market model determines the ex-vessel price for that

TABLE 4.1.1
 SAMPLE INPUT PORTION OF TERMINAL SESSION
 exec fishdyn1

M.I.T. SINGLE SPECIES, FISHERY SIMULATOR INVOKED
 PLEASE ENTER REPORT TITLE: Sample Demonstration run for SEA GRANT final report.
 PLEASE ENTER SPECIES NAME: YEL
 PLEASE ENTER RECRUITMENT OPTION: 4
 DO YOU WANT TERSE(T), SHORT(S), LONG(L) OR VERBOSE(V) OUTPUT?: TERSE
 ENTER ANY CHANGES TO SPECIES DATA: SPECIES.TAUMAX=2000;
 PLEASE ENTER VESSEL EFFORT OPTION: 2
 ENTER NO. OF VESSELS BY CATEGORY FOR 1976
 : 0 10 0 0 1
 ENTER NO. OF VESSELS BY CATEGORY FOR 1977
 : 0 10 0 0 1
 ENTER NO. OF VESSELS BY CATEGORY FOR 1978
 : 0 10 0 0 1
 ENTER NO. OF VESSELS BY CATEGORY FOR 1979
 : 0 15 0 0 1
 ENTER NO. OF VESSELS BY CATEGORY FOR 1980
 : 0 20 0 0 1
 ENTER NO. OF VESSELS BY CATEGORY FOR 1981
 : 0 20 0 0 0
 PLEASE ENTER CATCH OPTION: 1
 PLEASE ENTER ANY CHANGES TO VESSEL CHARACTERISTICS: FUELCST=140.00;
 PLEASE ENTER QUOTA OPTION: 1
 ENTER ANNUAL QUOTA IN METRIC TONS: 10000

list yel2.data nonum
YEL2.DATA

YELLOWTAIL FLOUNDER TEST DATABASE 2. FROM ICNAF SUMMARY DOC.
76/VI/8. 1975 POP EST IN MILLIONS.OCCURRENCE HIGHLY BOTTOM
DEPENDENT. ALSO EIS/FISHERY MANAGEMENT PLAN FOR GROUND FISH.
RICKER FORM MAX. LIKELIHOOD ESTIMATORS BASED ON PARACK PAPER
63-75 DATA, 11 SAMPLES, 2 YEAR OLDS LAGGED TWO YEARS.
DEMAND CURVE BASED ON HANKS 73 THRU 76 DATA
DEFLATED TO 75 DOLLARS BASED ON CPI FOOD INDICATOR
TRANSLATED, HYPERBOLIC LEAST SQUARES FIT .

YELLOWTAIL FLOUNDER		2	11															
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15			
0.00	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20			
51.1	48.9	29.9	11.6	5.5	2.01	.804	.172	.076	.029	.001								
154	358	521	696	846	965	1061	1131	1172	1213									

RECRUITMNT		1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
GATES-NORT	123	123	123	123	123	123	123	123	123	123	123	123	123	123	123
PARACK AVE	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
OPTION 3															
OPTION 4															
OPTION 5															
OPTION 6															

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CATCHABILITY		.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
LOW END ON DEMD		450	450	450	450	450	450	450	450	450	450	450	450
HI END ON PRICE		1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600
HI END ON DEMND		2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
LOW END ON PRIC		330	330	330	330	330	330	330	330	330	330	330	330
RICKER MLE'S		1.3189296E+01	-7.0320156E-02	3.3292430E-02									9
RICK B1 & RICKM		2.5794056E+00	3.3500000E+02										
NINVERSE		3.2746880E+00	-1.1184675E-01										
		-1.1184675E-01	3.9291977E-03										

TABLE 4.1.2

SAMPLE SPECIES FILE. THIS IS THE SPECIES FILE ACTUALLY USED
IN THE YELLOWTAIL FLOUNDER PRODUCTION RUNS OF CHAPTER 5.

month on the basis of aggregate round-weight landings of all ages of fish of the species in that month. In the New England groundfish fisheries, fish of certain sizes (e.g. large flounder, medium-sized "market cod," etc.) command significant premiums over this "average price." The age premiums in this line are applied to the average price as determined by the market routine before computing fisherman revenues and consumer surplus. This extremely ad hoc procedure has a number of obvious limitations, both practical and theoretical. But the alternative of generating separate but coupled demand curves for each major age group within a species was rejected at this time--basically on the grounds that we must learn to walk before we can run. In any event, if one is prepared to ignore intraspecies price differentials with age, the age premium row can be set to zero as shown in Table 4.1,2.

The next section of each species file contains a number (up to six) of exogenous recruitment hypotheses. These are used only if the model is operating in recruitment mode A, in which case the user must specify which of these hypotheses he desires for each particular run, or he may input an entirely different hypothesis from the terminal. The first line in this section serves to identify the year to which each set of numbers refers. Also, the first year and the last year of the simulation are taken from the first and last elements of this row, unless explicitly altered from the terminal by the user. Each exogenous recruitment hypothesis is given in the next six rows in

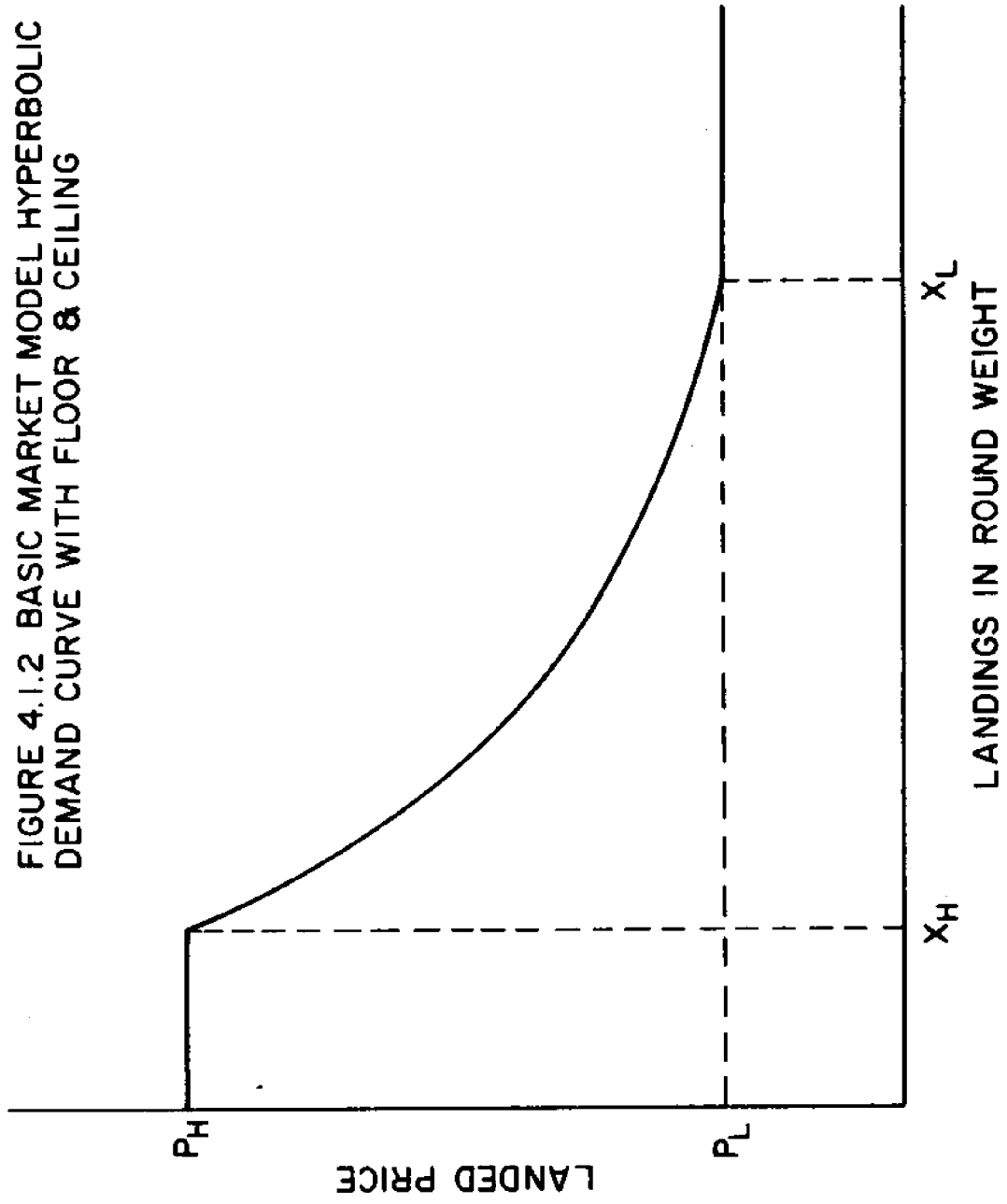
millions of recruits per year. Recruitment for up to the next fourteen years can be specified exogenously in this manner.

The next section of each species file contains monthly dependent data. The row labelled CATHCHABILITY is designed to address seasonal differences in catchability due to schooling during spawning, weather, etc. The CATCH routine adjusts the monthly catchability in terms of catch per lone effort per population by 1.00 plus the number shown.* If the user wishes to assume no seasonal variation in catchability, this row should be set to zero as it has been in Table 4.1.2.

The last four lines specify the market demand curves for each month for the subject species. Currently, the model employs a very simple description of market demand. As shown in Figure 4.1.2, the model assumes there is a lower level on ex-vessel price, p_L , at which demand becomes perfectly elastic. For the New England groundfish species, this lower level is set by the landed prices at which domestic landings would be competitive with imports in the frozen block market. Currently, this price is about 30-35¢ per kilogram round weight ex-vessel. The frozen block market is so much larger than current or potential landings of Georges Bank groundfish that there is little likelihood

*Lone effort refers to the catch a vessel would obtain if it were the only vessel exploiting the stock. See Section 4.3 for a more complete discussion of the concept.

FIGURE 4.1.2 BASIC MARKET MODEL HYPERBOLIC
DEMAND CURVE WITH FLOOR & CEILING



that these landings could affect the block price even if--as has not happened in the last five years--domestic landed price dropped to this level. Hence, one can make a strong case for the elasticity of the rightmost portion of the demand curve.

We also assume, as shown in Figure 4.1.2, that there is an upper level on price, p_H , beyond which no one will purchase the species, i.e. demand again turns elastic. This assumption is more an analytical convenience than an empirical reality.* As is argued later, all available evidence indicates that the short-run demand for flounder, haddock, and, to a somewhat lesser extent, cod becomes increasingly inelastic as landings decrease. When landings are low, all these premium species go to restaurants and specialty fish markets serving high-income customers for whom price is a secondary consideration. We simply don't know just how high the price for these species would go if the supply became low enough.

In practice, then, p_H is set at or a little above the highest price ever observed and the demand curve cut off at this point. This also cuts off consumer surplus at this point. However, as we argued in Chapter 2, we are only interested in changes in consumer surplus associated with alternative management policies. Hence, this cut-off

*A possible exception is herring. In this case, the upper price may well be the ex-vessel price at which domestic herring is competitive in the large European foodfish market, in which case demand may very well turn elastic at this level.

assumption will have no effect on our results as long as landings do not drop below the level corresponding to p_H . In the terminology of Chapter 2, p_H and the corresponding level of landings, x_H , are the baseline against which changes in consumer surplus are measured. If in a particular simulation, we generate landings which are lower than x_H , this cut-off assumption will result in an underestimation of the consumer surplus effect. This will have to be kept in mind in interpreting our results.

In any event, having established an upper ex-vessel price level, p_H , and a lower price level, p_L , and the corresponding level of monthly landings, x_H and x_L , the market model assumes a hyperbolic demand curve between these two points as shown in Figure 4.1.2. The four numbers, (p_H, x_H) and (p_L, x_L) , for each month constitute the correspondingly labelled four lines of each species data file. The first of these lines contains x_H for each month in metric tons round weight; the next contains p_H in dollars per metric ton; and the next two contain x_L and p_L respectively. In the file shown in Table 4.1.2, the user has assumed no seasonal variations in demand. The final section in each species file contains the recruitment information used when FISHDYN1 is operated in recruitment modes B and C. The line labeled RICKER MLE's contains the two maximum likelihood estimators for the Ricker-form parameters followed by the sample

variance and the sample size of the sample of historical stock-recruitment data to which the Ricker form was fitted. The final two lines contain the inverse of the sample moment matrix which is required by the Monte Carlo recruitment sampling routines.*

Returning to the input from the terminal, Table 4.1.1, we note that after reading in the user-selected species file, the model asks which recruitment option the user desires to run and then prompts for any changes to the species data. At this point, the user may temporarily alter any element of the species data file for this particular run.** It is at this point that the user must specify a mesh-size limitation, if desired.

The model has four output options:

1. TERSE. The model will perform the entire simulation, after which it prints out a brief overall summary such as that shown in Table 4.1.3 in which only one line is devoted to each year in the simulated period.
2. SHORT. In addition to the above, the model prints out an annual summary for each simulated year showing the total annual catch by age and the resulting year-end, residual population and biomass by year class. Table 4.1.4 displays a typical SHORT summary for two succeeding years. If there are twenty years in the simulation, SHORT will

*All these statistics are generated by the program RICKER, which operates off-line from FISHDYN1 proper. This procedure is described in Section 4.5 below.

**If the user wishes to make a permanent or semi-permanent change to a species file, this is easily accomplished by editing the file from the terminal prior to invoking the model.

TABLE 4.1.3

COMPLETE OUTPUT OF A RUN WITH "TERSE" OPTION

Sample Demonstration run for SEA GRANT final report.
 SPECIES NAME: YELLOWTAIL FLOUNDER
 INITIAL CONDITIONS AS OF JAN 1 INITIAL YEAR AFTER YEAR END AGING. POPULATION IN MILLIONS. BIOMASS IN METRIC TONS.
 AGE CLASS 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 TOTAL
 NAT. MORT. RATE 0.00 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 770922
 WT AT AGE (GRAMS) 0 154 358 521 696 846 965 1061 1131 1172 1213 1213 1213 1213 1213 99.0
 NUMBERS 51.1 48.9 29.9 11.6 5.5 2.0 0.8 0.2 0.1 0.0 0.0 0.0 0.0 0.0 0.0 30886
 BIOMASS 7531 10704 6044 3828 1700 776 182 86 34 1 1 1 1 1 1 1

RICKER FORM RECRUITMENT ASSUMED. MLE OF ALPHA= 1.31893E+01 MLE OF BETA= 7.03202E-02 SAMPLE SIZE= 11 VARIANCE(LOG)= 3.32924E-02

MARKET ASSUMPTIONS--MAXIMUM PRICE IS BASELINE FOR CONSUMER SURPLUS CALCULATIONS. PRICES IN \$/METRIC TON FOUND WEIGHT.
 JANUARY FEBRUARY MARCH APRIL MAY JUNE JULY AUGUST SEPTEMBER OCTOBER NOVEMBER DECEMBER
 UPPER BOUND ON PRICE 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00 1600.00
 LOWER BOUND ON PRICE 330 330 330 330 330 330 330 330 330 330 330 330 330 330 330 330
 UPPER BOUND ON CATCH 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000

VESSEL CHARACTERISTICS ASSUMED FOR THIS SIMULATION.

FUEL PRICE(\$/MT)=140.00 UNLOADING COST(\$/MT)= 0.00 ICE PRICE(\$/MT)= 20.00 SOCIAL COST OF CAPITAL= 0.05
 IND GRT BHP GEAR FISH ICE RUN- FUEL TON- TOW. NET MAX CREW INIT ANN. ANN. CPEN ANN. MOOR VES- PEL. AVE. ANN. MAX DIST
 -EX HOLD LOAD ING CSMF ING FUEL AREA CAT. SIZE COST INSP. WANT ADMN OPP. GALL -AGE SEL FISH MAX. DAYS TRIP TO
 SIZE SPD TON/ SPD TON/ SQ. TON/ KILO COST COST COST COST COST LIFE POW- CATCH AT LNTH FISH
 TONS TONS KNTS DAY KNTS DAY MTPS TON \$ S (THOUSAND DOLLARS PER YEAR) EP T/DAY SEA DAYS CPND
 2 125 480 0TB2 75 10 10.0 2.50 0.0 0.00 0 0 5 250 10 20 20 50 15 0 20 0.00 7 225 10 0
 2 CATCH VARIATION= 0.50 DAYS FISHED PER DAYS ABSENT= 0.67 MONTHLY FIXED EXPENSES= 8333 MONTHLY VARIABLE EXPENSES= 8184

YELLOWTAIL FLOUNDER

Sample Demonstration run for SEA GRANT final report.

YEAR	INITIAL CATCH BIOMASS	RECRUIT BIOMASS	INITIAL CATCH POP.	RECRUIT POP.	YEAR END BIOMASS	YEAR END POP.	FLEET QUOTA	CONSUMER SURPLUS	FISHERMEN REVENUE	OPERATING OUTLAYS	NEW INVESTMENT	AVG AGE PRICE
1976	30886	5231	99	17	58	10	10000	0	8370	1982	2500	1600.00
1977	36630	5237	51	16	68	10	10000	0	8379	1982	0	1600.00
1978	44020	5244	58	15	82	10	10000	0	8390	1982	0	1600.00
1979	51084	5127	48	131	80	15	10000	8780	7870	2973	1250	1002.69
1980	50592	10430	37	117	63	20	10000	11531	8435	3964	1250	808.76
1981	42322	10401	30	93	45	20	10000	11507	8429	3964	0	810.38
1982	32924	10343	33	78	31	20	10000	11558	8416	3964	0	813.70
1983	24935	10231	46	76	20	20	10000	11462	8392	3964	0	820.18
1984	19320	9990	60	80	9	20	10000	11239	8339	3964	0	834.72
1985	14572	8315	70	78	4	20	10000	8486	7790	3964	0	936.84
1986	11723	6880	67	70	2	20	10000	6683	6666	3964	0	958.81
1987	9876	5900	61	36	1	20	10000	5357	5945	3964	0	1007.63
1988	8524	5151	52	53	1	20	10000	4854	5354	3964	0	1039.36
1989	7531	4587	47	48	1	20	10000	4050	4788	3964	0	1043.76
1990	6746	4130	42	43	1	20	10000	3400	4469	3964	0	1082.12
1991	6134	3772	39	39	0	20	10000	3119	4114	3964	0	1090.79
1992	5624	3467	35	36	0	20	10000	2557	3954	3964	0	1140.68
1993	5211	3220	33	33	0	20	10000	2406	3691	3964	0	1146.29
1994	4854	3006	31	31	0	20	10000	2237	3472	3964	0	1154.69
1995	4554	2823	29	29	0	20	10000	2051	3328	3964	0	1178.75
1996	4292	2663	27	27	0	20	10000	1638	3280	3964	0	1231.66
1997	4066	2526	26	26	0	20	10000	1480	3131	3964	0	1239.51
1998	3865	2403	25	25	0	20	10000	1400	2997	3964	0	1247.44
1999	3689	2295	23	23	0	20	10000	1400	2881	3964	0	1255.21
2000	3530	2197	22	22	0	20	10000	1316	2785	3964	0	1267.55

TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.

CHANGE IN CONSUMER INCOME= 77686 CHANGE IN FISHERMEN INCOME= 39154 CHANGE IN REAL NATIONAL INCOME=

116840 RUN NO. 1

ANNUAL SUMMARY FOR YEAR 1976										RECRUITMENT AT BEGINNING(JAN 1, 1976) OF AGE 2 =										0.0 MILLION FISH										ANNUAL QUOTA=									
CONSUMER SURPLUS= 10781583										FISHERMEN REVENUE= 7367083										OPERATING OUTLAYS= 4922068										NEW INVESTMENT=									
STANDING STOCK NUMBERS ARE AT END OF YEAR(DEC 31, 1976) PRIOR TO AGING.										TOTALS REFER TO AGE 2+ FISH ONLY.										2+ FISH ONLY.										10000									
AGE GROUP 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15										TOTAL										6750000																			
NUMBERS 0.0 51.1 18.3 11.2 4.3 2.1 0.8 0.3 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0										37.1										10000																			
BIOMASS 2823 4013 2266 1435 637 291 68 32 0 0 0 0 0 0 0 0										11578										6750000																			
NAT MFT 0.0 0.0 14.4 8.8 3.4 1.6 0.6 0.2 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0										29.1										6750000																			
CATCH NO. 16.2 9.9 3.8 1.8 0.7 0.3 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0										32.8										6750000																			
CATCH WT. 2495 3547 2003 1268 563 257 60 28 0 0 0 0 0 0 0 0										10234										6750000																			
VESSEL CATEGORY 1 2 3 4																																							
NO. OF ACTIVE VESSELS 20 5 2 1																																							
NO. OF NEW VESSELS 20 5 2 1																																							

ANNUAL SUMMARY FOR YEAR 1977										RECRUITMENT AT BEGINNING(JAN 1, 1977) OF AGE 2 =										51.1 MILLION FISH										ANNUAL QUOTA=									
CONSUMER SURPLUS= 10725101										FISHERMEN REVENUE= 7346759										OPERATING OUTLAYS= 4922068										NEW INVESTMENT=									
STANDING STOCK NUMBERS ARE AT END OF YEAR(DEC 31, 1977) PRIOR TO AGING.										TOTALS REFER TO AGE 2+ FISH ONLY.										2+ FISH ONLY.										10000									
AGE GROUP 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15										TOTAL										0																			
NUMBERS 0.0 62.9 15.5 5.4 3.4 1.3 0.6 0.2 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0										26.6										10000																			
BIOMASS 2391 1924 1767 905 529 220 99 22 0 0 0 0 0 0 0 0										7872										10000																			
NAT MFT 0.0 0.0 16.0 5.7 3.5 1.4 0.6 0.2 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0										27.6										10000																			
CATCH NO. 19.6 7.2 4.3 1.7 0.8 0.3 0.1 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0										34.1										10000																			
CATCH WT. 3020 2582 2248 1175 670 280 121 28 0 0 0 0 0 0 0 0										10141										10000																			
VESSEL CATEGORY 1 2 3 4																																							
NO. OF ACTIVE VESSELS 20 5 2 1																																							
NO. OF NEW VESSELS 0 0 0 0																																							

TABLE 4.1.4
SHORT OUTPUT FOR TWO SUCCEEDING YEARS UNDER "SHORT" OPTION

generate twenty such annual summaries.

3. LONG. In addition to the output provided by SHORT, the program prints out a monthly summary for each year, showing total catch per month, the resulting monthly prices and monthly cash flows. Table 4.1.5 displays a typical LONG summary for a single year.
4. VERBOSE. In addition to the output provided by LONG, the model prints out the catch by age for each month and year. Table 4.1.6 displays this output form for a single year.

Returning once again to Table 4.1.1, after ascertaining the user's desires with respect to amount of output, DRIVER prompts for information with respect to effort. In so doing it refers to the Vessel Data File (VDF). A typical VDF is shown in Table 4.1.7. The Vessel Data File contains one line of data for each vessel type which may (potentially) fish the species. Current programming can handle up to twenty vessel types. The VDF shown contains four. Most of the entries in this file are self-explanatory. One entry that is not is Crew Opportunity Cost (CREW OPP. COST). This column should contain estimates of what the crew's annual earned income would be if the crew could not fish. Depending on the user's alternative employment assumptions, this could range from top blue-collar income in, say, the offshore oil industry to near zero if one believes the best the crew could do were it not fishing is permanent welfare. Annual crew earnings above this amount are included in the fisherman surplus. This definition of Crew Opportunity Cost is consistent

ANNUAL SUMMARY FOR YEAR 1977 RECRUITMENT AT BEGINNING (JAN 1, 1977) OF AGE 2 = 51.1 MILLION FISH ANNUAL QUOTA = 10000
 CONSUMER SURPLUS = 9852473 FISHERMEN REVENUE = 8046221 OPERATING OUTLAYS = 3735278 NEW INVESTMENT = 0
 STANDING STOCK NUMBERS ARE AT END OF YEAR (DEC 31, 1977) PRIOR TO AGING. TOTALS REFER TO AGE 2+ FISH ONLY. 13 14 15 TOTAL

AGE GROUP	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTAL
NUMBERS	0.0	61.5	21.3	8.7	5.4	2.1	1.0	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.1
BIOMASS	0.0	0.0	3276	3125	2834	1458	848	352	157	35	16	7	0.0	0.0	0.0	0.0	12109
NAT MFT	0.0	0.0	14.8	6.2	3.8	1.5	0.7	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.2
CATCH NO.			15.1	6.4	3.8	1.5	0.7	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.9
CATCH WT.			2322	2297	1998	1045	595	249	107	25	11	4					8654

VESSEL CATEGORY 1 2 3 4
 NO. OF ACTIVE VESSELS 10 5 2 1
 NO. OF NEW VESSELS 0 0 0 0

MONTHLY SUMMARY FOR 1977

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
MILLION FISH CAUGHT	2.30	2.34	2.34	2.34	2.34	2.33	2.33	2.33	2.33	2.32	2.32	2.31
METRIC TONS CAUGHT	716	726	725	724	724	723	722	721	720	719	718	716
AVERAGE PRICE (\$/MT)	935	925	926	927	927	928	929	930	931	932	933	935
FISHERMEN REVENUE	669406	671469	671352	671222	671081	670921	670742	670543	670312	670050	669744	669385
VARIABLE OUTLAYS	311274	311274	311274	311274	311274	311274	311274	311274	311274	311274	311274	311274
CONSUMER SURPLUS	814881	826263	825624	824918	824147	823267	822866	821189	819918	818464	816765	814761

TABLE 4.1.5
 SAMPLE OUTPUT FOR A SINGLE YEAR UNDER LONG OPTION


```

list ves1.data nonum
VES1.DAT
VESSEL CHARACTERISTICS FILE #1 (VES1). ALL FIGURES IN 76 DOLLARS. LAST UPDATA DEC XX, 1976.
NO. OF VESSEL CATEGORIES= 4 FUEL PRICE($/MT)=120.00 UNLOADING PRICE($/MT)= 0.0 ICE PRICE($/MT)= 20.00
LWL GRT BHP. GEAR HOLD ICE PUN. FUEL TON. TON. NET MAX CREW INIT.INSR MANT ADMN CREW GALL MOOR VES. REL. AVE. DAYS MAX. DST
M. SIZE LOAD SPD. CMP. SPD. FUEL AREA CAT/ SIZE COST COST COST COST COST COST COST COST COST AT TRIP TO
TONS TONS KNTS T/D KNTS T/D SQ.M TOW 5 180 8 18 20 50 13 0 20 5.0 225 10 0
1 18 75 325 OTB1 30 5 9.0 1.60 5 250 10 20 20 50 15 0 20 7.0 225 10 0
2 21 125 480 OTB2 75 10 10.0 2.50 13 550 20 35 25 150 35 0 20 10.0 225 10 0
3 32 198 850 OTB1 125 20 11.0 4.25 13 800 30 50 25 150 35 0 20 12.0 225 10 0
4 36 311 1300 OTB2 175 30 13.0 6.50

```

TABLE 4.1.7.

SAMPLE VESSEL DATA FILE. THIS IS THE VDF ACTUALLY USED
IN THE YELLOWTAIL FLOUNDER PRODUCTION RUNS OF CHAPTER 5.

with our desire to compute a total fisherman surplus in which both vessel owners and the actual fishermen are lumped into the single category "fishermen". It also implies that FISHDYN1 makes no attempt to simulate how fisherman surplus is divided between capital (the vessel owners) and labor.*

Returning once again to the terminal session shown in Table 4.1.1 after reading the Vessel Data File into core memory, the program asks the user a number of questions with respect to this file and its use. First, it asks the user to specify how many vessels of each type will be exploiting the fishery in each year of the simulation. In the run shown in Table 4.1.1, the user has responded that he wished to see what would happen if the initial active fleet directed at this fishery consisted of thirty full-time vessels of category 2 (category 2 is 125 GRT stern trawlers, as can be seen from Table 4.1.7) decreasing to twenty such vessels in the fifth year of the simulation and remaining at that level afterwards. No other vessel types are to be included in this run. The relationship of this set of inputs to our "exogenous control" premise is obvious.

Internally, the program potentially contains a number of different effort-catch formulations, each of which is known as a "Catch Option." Currently, only one catch option has

*In this industry, the lay system and the fact that owner and labor are often the same person makes any such division largely artificial. More importantly, the actual form of this division has almost no management policy implications. Despite this fact, much effort has been wasted in the study of the lay system, usually attempting to prove that the lay system is the cause of the industry's severe undercapitalization, when in fact the industry is sharply overcapitalized, as we shall see.

been implemented. Catch Option 1 is a simple Carlson vessel conflict model in which the catch of an individual vessel if it were operating completely alone is estimated and then total catch of a fleet obtained by assuming that each vessel's catch is reduced by the proportion of fish caught by others.

After obtaining the Catch Option, the program asks for any changes in the vessel characteristics. At this point, the user can temporarily change any of the elements in the VDF. For example, he might ask: what will happen if fuel prices double? Finally, the program asks for an annual quota if any. The default is no quota. The user may enter a different quota for each year or, as shown in Table 4.1.1, an annual quota which will remain constant throughout the run.

Having obtained the response to the quota query, the program will immediately proceed to the simulation. Ordinarily, response is practically instantaneous and total terminal time to run a single case is of the order of a minute or two, and costs about \$1.00.

4.2 Overall description of DRIVER

In concept, DRIVER is completely straightforward. Most of the code is taken up with input and output but basically the program consists of two loops: a loop over years, and within this loop a loop over months. At each iteration of the monthly loop, DRIVER has available to it the current

population distribution by age in terms of numbers of fish. It also knows the current level of effort in number of boats of each category specified by the user. It transmits this information to subroutine CATCH which responds with a CATCH in numbers by age. DRIVER combines this fishing mortality with the user-specified natural mortality which generates the population at the end of the month; whereupon the process repeats itself.

DRIVER does have one unhappy idiosyncrasy. In the model as it now stands, all recruitment and growth are assumed to take place once a year, on January 1. On January 1, the population is aged a year, generating a year's worth of individual fish growth, and the entering class is fully recruited overnight. This implies that on a stock that's being very heavily exploited, the bulk of the catch occurs in the earlier part of the year. An obvious improvement would be to have growth and recruitment occur monthly (with perhaps seasonal fluctuations) generating a considerably better picture of reality.

A sample of the monthly population updating process is shown in Table 4.1.6. When the catch level for each year class is returned from subroutine CATCH it is converted to a monthly fishing mortality rate, $F(t)$, and this rate plus the user-supplied natural mortality rate, $M(t)$, for the corresponding age group is applied to the

year-class population. That is, within each month we are assuming exponential decrease in population at a rate of $F(t) + M(t)$ for each age group t .

4.3 Description of the CATCH subroutine

The CATCH submodel proceeds as follows.

1. First the submodel estimates how much an individual vessel in each size category would catch in a month, if it were the only vessel fishing the current total adult biomass, WB.
2. The individual catch for each vessel category j is converted to a proportion of the current stock. The total monthly catch, C , for a fleet consisting of N_j vessels of each size category is estimated to be

$$C = WB \cdot \prod_{j=1}^J (1 - q_j)^{N_j}$$

The reasoning behind this multiplicative model of vessel interference is that if one vessel catches a proportion q_j of the biomass, then two vessels will catch something less than $2 \cdot q_j$. This model, introduced by Carlson [1969] and generalized by Gates and Norton [1974] assumes two vessels would catch $q_j + q_j(1 - q_j)$. In other words, the second vessel operates on only that portion of the biomass not caught by the first. Generalizing this reasoning to N_j vessels in each vessel category and J categories leads to the above expression. Philosophically, the vessel interference model in FISHDYN1 is a direct copy of the Gates and Norton interference model.

With respect to the catch of an individual vessel operating alone, CATCH assumes that on a given trip, the vessel is limited either by its fish hold capacity or by the areas which it can sweep with its net. Part of the Vessel Data File input, for each vessel category, is the AVMAXCT (Average Maximum Catch) variable in tons per day. This should be set to the fish hold size divided by the days fished on the longest individual trip for which the vessel was designed. For our Georges Bank yellowtail exercises, AVMAXCT has been set to fish hold capacity divided by 10. This, then, is a measure of the potential fishing capacity of the vessel.* To this number, the model applies a Catch Variation factor, CATVAR, between 0.00 and 1.00. The Catch Variation factor is an attempt to reflect the fact that even if a vessel were fishing a bountiful stock all by itself it could not expect to fill its hold on every trip. For the yellowtail exercises reported herein, the Catch Variation factor has been set to 0.50. This is based on conversations with owners to the effect that "in the good old days" a captain who came in with too many half-loads would be turned ashore. It also reflects the fact that the coefficient of variation in random trawl surveys has been measured at about 2. It is believed to be conservative. Even in the "good old days," stocks

*Of course, on any given day the vessel can catch much more than AVMAXCT.

were limited and no vessel was fishing by itself. And fishermen, unlike research surveys, do not sample randomly.*

The product of CATVAR times AVMAXCT times days fished per trip is compared with the product of area swept per trip times average concentration of the fish (adult biomass divided by the area of the fishery times a factor CONCENT which is supposed to represent the Concentration fished (as opposed to the above average concentration) times the proportion of fish swept to fish actually caught.** The area swept per trip is estimated from the net width and towing speed of each vessel category as well as the days fished per trip. For the exercises reported herein, the concentration factor has been arbitrarily set to 5 on the grounds that the area intensively fished for yellowtail is roughly 20% of the area of the Bank. Obviously, this parameter could bear more study. However, with the numbers used herein it turns out that for all but a very few low stock levels, the individual vessel catch operating alone was limited by AVMAXCT*CATVAR rather than by fish concentration.[†]

*Our ability to build a better CATCH model would be greatly enhanced if we had a histogram of catch per trawl or per day for a reasonably large sample of trips, such as the Japanese collect [Motte and Iitaka, 1975]. Lacking this, a good deal could be learned by analysis of individual trip catches.

**Area swept rather than volume swept was chosen for the strictly bottom-dwelling yellowtail. FISHDYN1 can handle either.

[†]Under our number, the concentration limit is about 1%. That is, a vessel operating alone can never catch more than 1% of the stock per trip. For a sixty-five foot dragger under our numerical assumption, the average maximum catch limit works out to about fifteen tons per trip. Therefore, the concentration limit applies only when the adult biomass drops below 1,500 tons, at which point the fishery is for all practical purposes wiped out.

In summary, the catch in tons per trip of an individual vessel of category j , L_j , is given by

$$L_j = \text{MIN}(\text{CATVAR} * \text{AVMAXCT} * \text{DAYFISH} * \text{TRIPLEW}, \\ \text{CONCENT} * \text{AREASWP} * \text{WB/AREA BND})$$

where DAYFISH is the ratio of the days fished to the days absent. This factor has been set to .67 in the yellowtail application which follows.

At present, FISHDYN1 allocates the total monthly catch to each fully recruited age group on a straight proportion of age group mass basis. That is, CATCH assumes no differences in gear efficiency for the fully recruited age groups.

4.4 Description of the MARKET routine

The function of the MARKET routine is quite simple. Each month, it is told how much fish was landed and it examines the demand curve to obtain the corresponding price. The demand curves used by the model have been developed by the following procedure:

1. Monthly landings and prices were obtained from the NMFS Fish Market News Reports ("blue sheets") for the period 1973 through 1976. Aggregate New England landings and Boston prices were used.
2. All prices were deflated to 1975 dollars using the Boston Consumer Food Price Index.
3. Scatter diagrams of monthly landings and (deflated) prices were prepared.*

*Interpreting such scatter diagrams as demand curves involves the assumption that short-run supply is completely inelastic over

Some of the results are displayed in Figures 4.4.1 through 4.4.5.

Several general comments are in order. For all the demersal species, the price of imported frozen block represents a floor. Currently, this price, translated to round weight, is roughly 15¢/lb or about 33¢/kg. Price cannot drop below this level. Therefore, if enough fish is landed so that the fresh-fish market is completely saturated, then the marginal fish must go to block and the price will drop to this level. Since domestic New England catch is very small compared with foreign imports, there is no way the domestic catch can affect the block price. Hence, once the price has dropped to the block level, it can drop no further. At these very high levels of landings, demand becomes perfectly elastic and hence the demand curve horizontal.

As the scatter diagrams indicate, this has rarely happened in the last four years. Almost all the high-value, domestically landed groundfish has been sold as fresh fish.* The reason is obvious. For most of this period, the fresh fish price has been well above the block price. Thus, we have not been on the horizontal part of the demand curve. In fact, as is clear from the scatter diagrams, demand becomes

the corresponding price range. This appears reasonable, since there has been excess existing capacity throughout this period, and given this excess, the marginal cost of operating a vessel has been well below the market price for the great bulk of the fleet.

*Pollock is the only New England groundfish that is fairly regularly sold to frozen-fish processors.

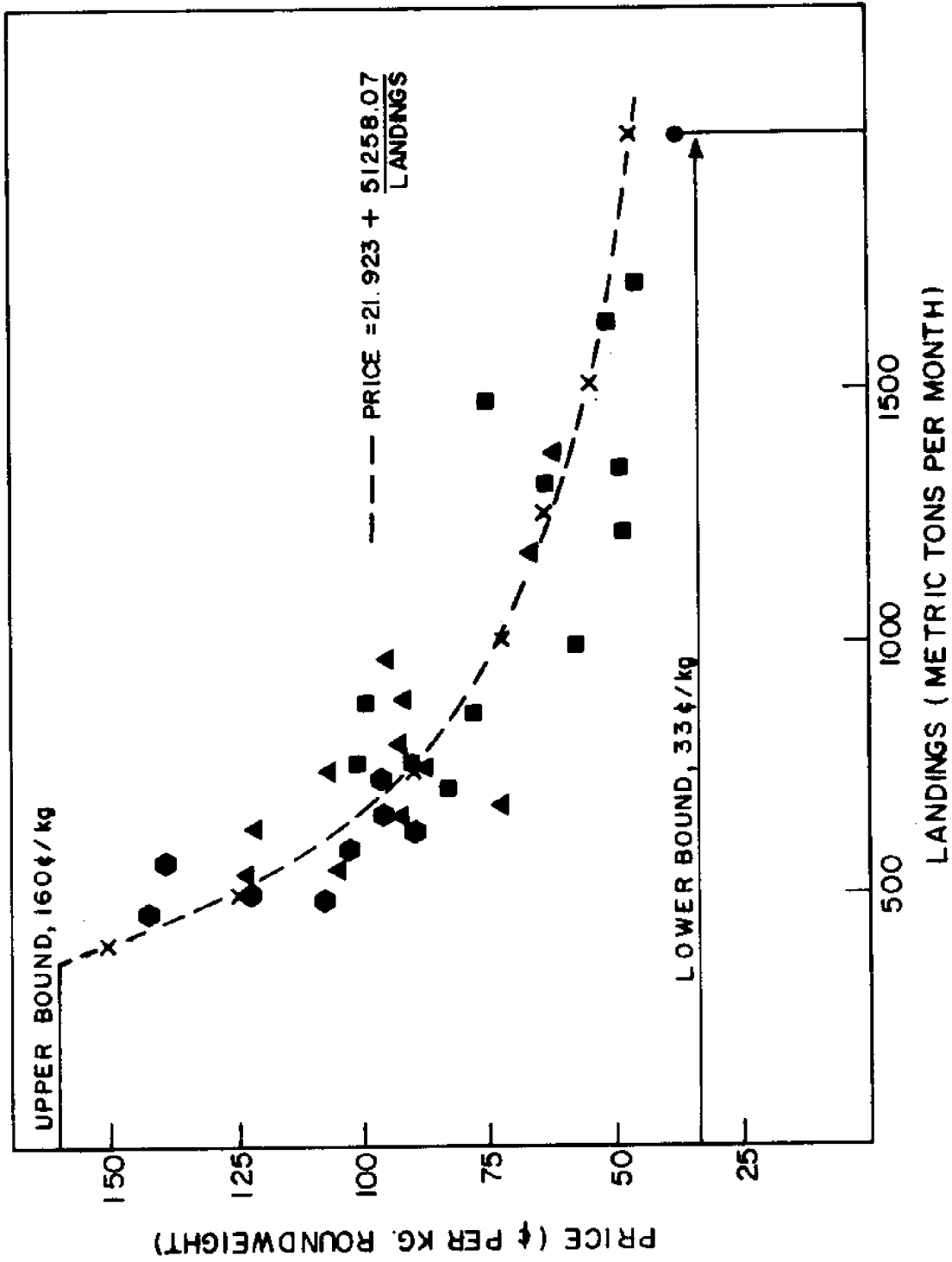


FIGURE 4.4.1 YELLOWTAIL FLOUNDER MONTHLY LANDINGS VS. EX-VESSEL PRICE 1973 THRU 1976 (ALL PRICES DEFLATED TO 1975 USING BOSTON CPI)

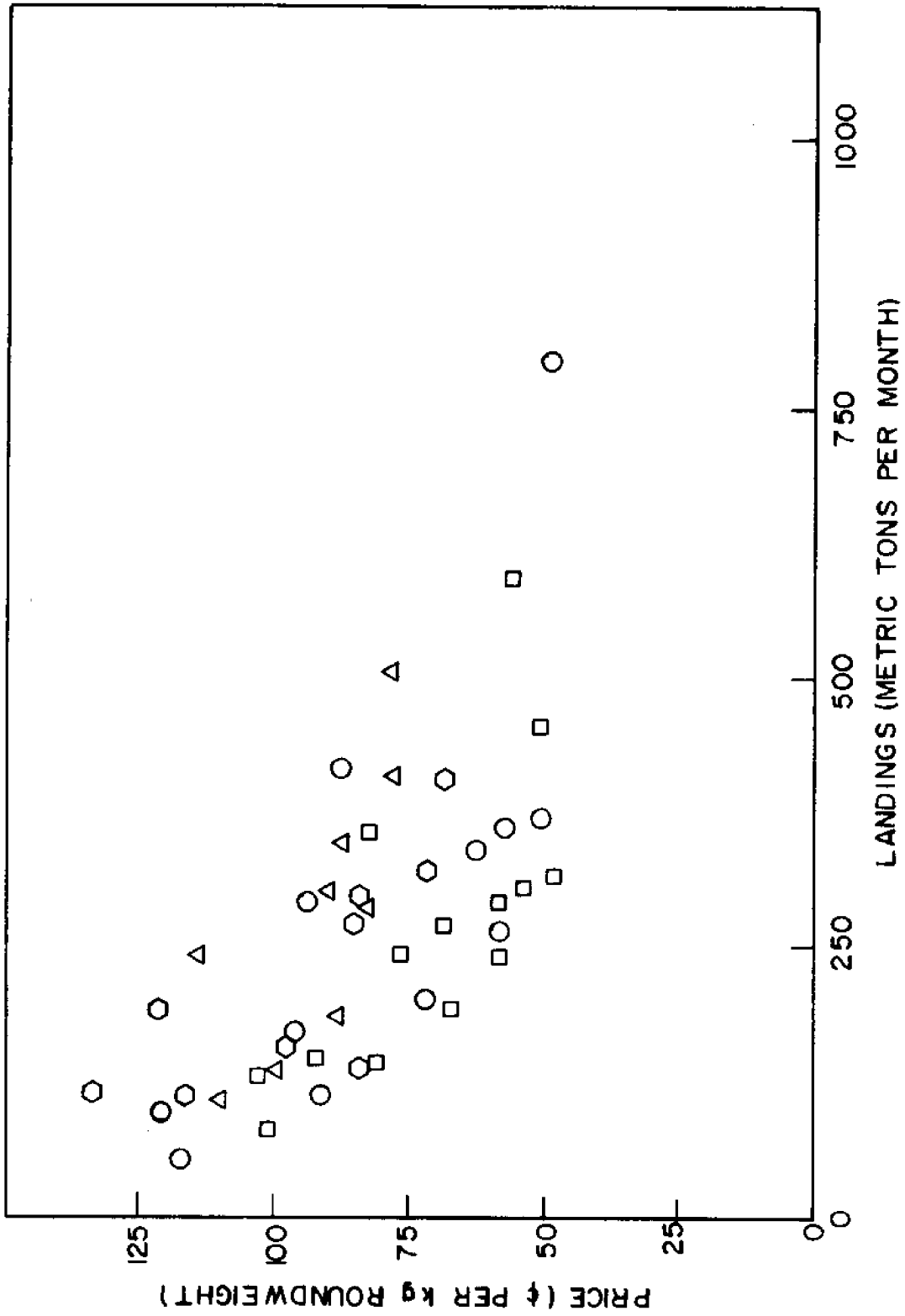


FIGURE 4.4.2 LARGE BLACKBACK FLOUNDER MONTHLY LANDINGS VERSUS EX-VESEL PRICE (ALL PRICES DEFLATED TO 1975 USING BOSTON CPI)

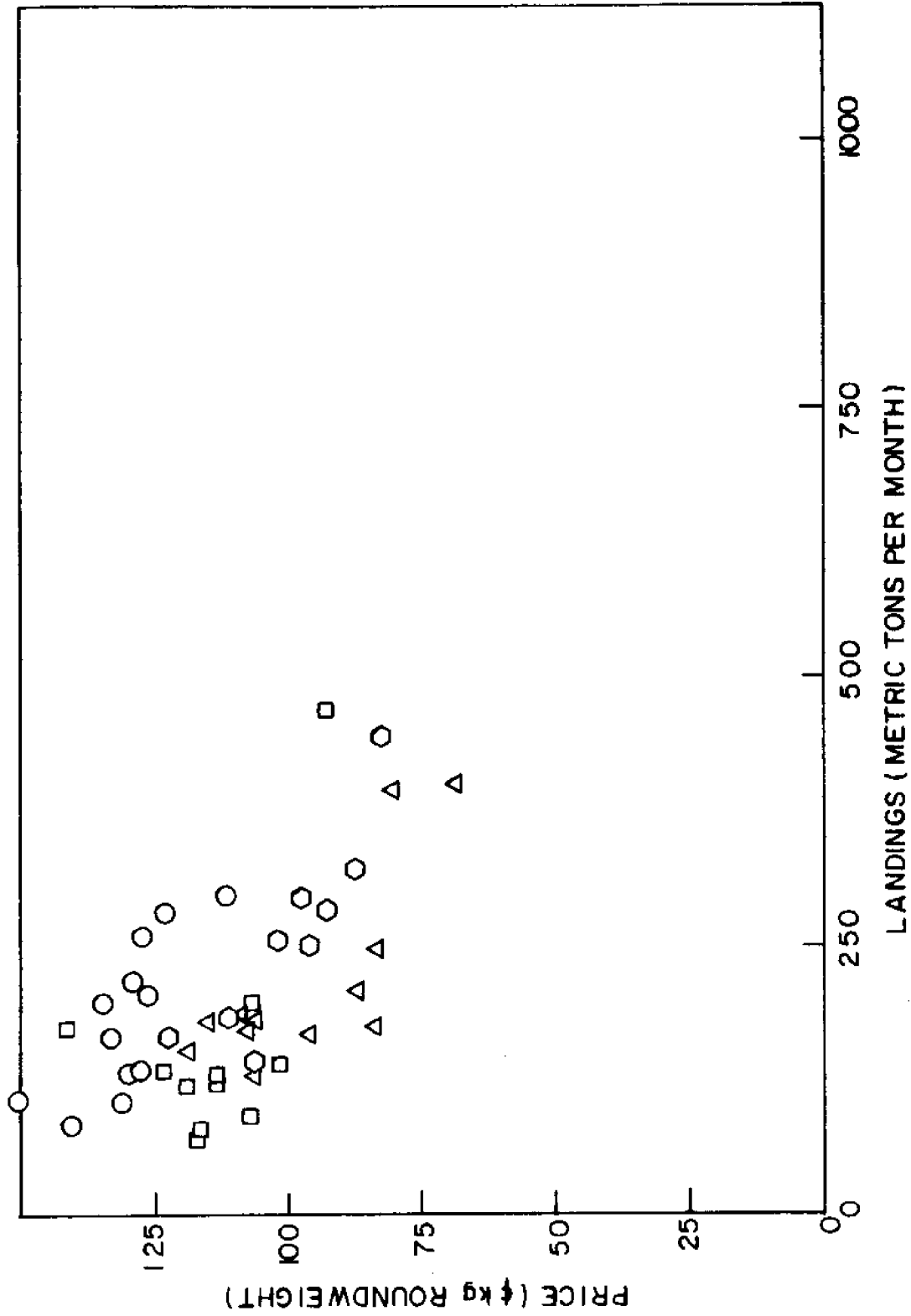


FIGURE 4.4.3 LARGE HADDOCK MONTHLY LANDINGS VERSUS EX-VESSEL PRICE

FIGURE 4.4.4. MARKET COD MONTHLY
LANDINGS VERSUS EX-VESEL PRICE

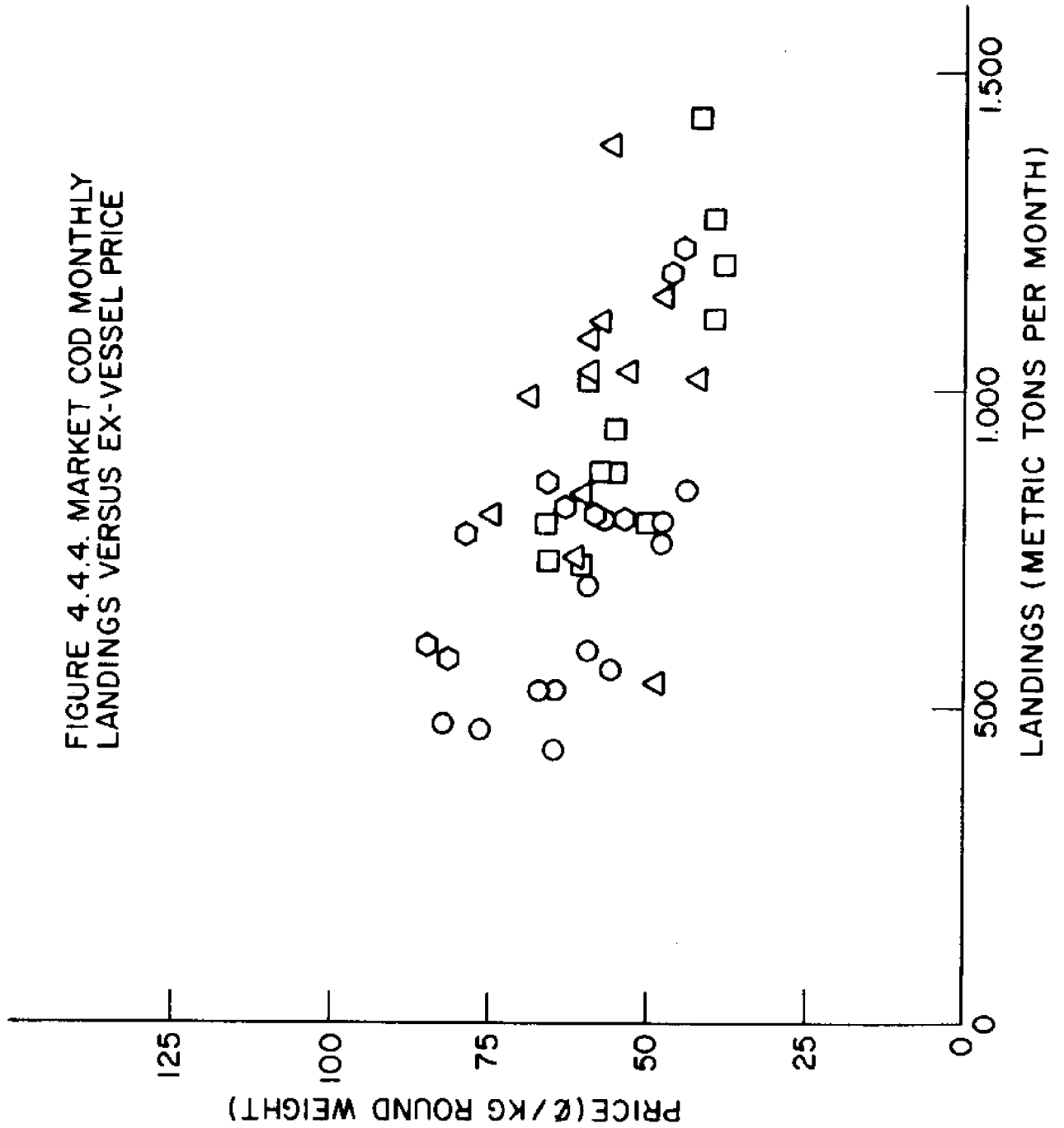
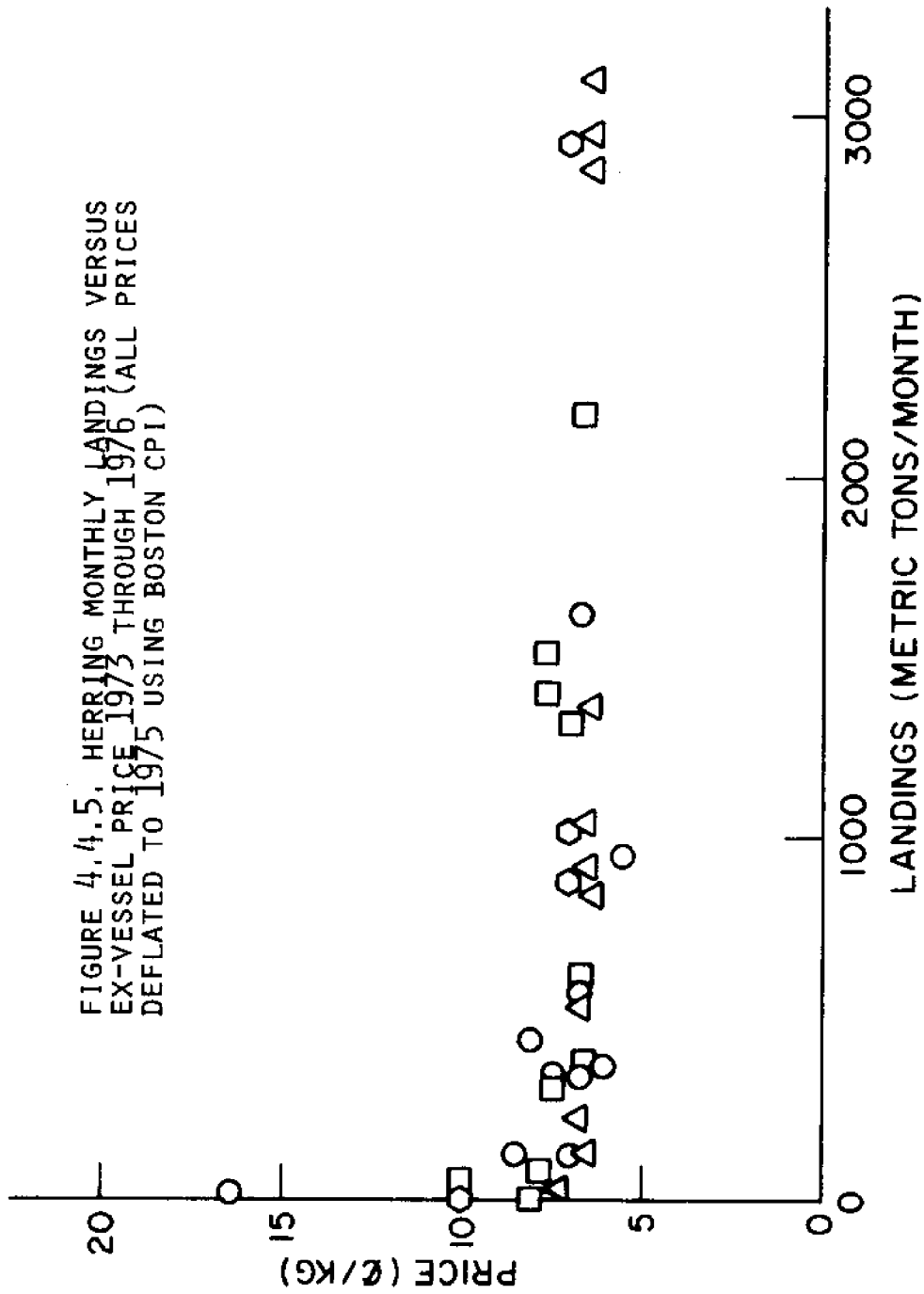


FIGURE 4.4.5. HERRING MONTHLY LANDINGS VERSUS
EX-VESSEL PRICE 1973 THROUGH 1976 (ALL PRICES
DEFLATED TO 1975 USING BOSTON CPI)



increasingly less price-sensitive as landings drop. This phenomenon is particularly apparent in the case of the yellowtail flounder, Figure 4.4.1. In recent months, landings have dropped to 500 tons per month, at which point demand is quite insensitive to price. At these low levels of landings, almost all yellowtail flounder is going to restaurants and premium fish markets, where it is resold to high-income groups. Apparently this market is willing to pay whatever it must to obtain the small amounts of yellowtail which are available. Prices of 55¢ per pound have become quite common and prices as high as 80¢ per pound have been observed.

The relative inelasticity of price at low levels of landings for premium groundfish is the explanation for the reigning paradox of the New England groundfish industry: the stocks have never been in worse shape but the fishermen have never done better.

The importance of landed price to fisherman income is illustrated by Table 4.4.1. This table estimates all non-labor costs for a seventy-five ton, side-trawling dragger--the mainstay of the New England yellowtail fleet and FISHDYN1 vessel category 1. At 7.5% real (equivalent to a market interest rate of 12+%), the present value of all these expenses for fifteen years is about one million dollars. The cost assumptions are for the most part generous, especially if one assumes a Gulf of Mexico-built vessel. The bottom portion of the table indicates the annual surplus

TABLE 4.4.1
 SAMPLE ECONOMICS OF NEW ENGLAND DRAGGER
 (ALL VALUES IN 1976 DOLLARS)

Vessel Characteristics

Length	65'
Gross registered tonnage	75
Fish capacity	30 tons
Crew	5
Potential catch	~ 900 tons/year
Economic life	
Real cost of capital	7.5%
Present-value non-labor cost	\$1,013,000
Initial cost	\$180,000
Annual insurance cost	\$8,000
Annual maintenance	\$18,000
Annual stores	\$13,000
Administration/overhead/miscellaneous	\$20,000
Fuel price	\$120/ton
Annual fuel cost	\$50,000
Ice price	\$20/ton
Annual ice cost	\$4,000

<u>Catch Per Year Tons</u>	<u>Average Price \$/Lb</u>	<u>Present-Value Revenue</u>	<u>Annual Surplus</u>
150	.10	291,000	-87,000
	.20	582,000	-54,000
	.40	1,165,000	11,000
	.60	1,747,000	77,000
300	.10	582,000	-54,000
	.20	1,165,000	11,000
	.40	2,330,000	143,000
	.60	3,445,000	275,000
600	.10	1,665,000	11,000
	.20	2,330,000	143,000
	.40	4,660,000	407,000

for this vessel as a function of annual catch and average landed price. This surplus is the money available to be distributed to the crew and owner above and beyond the 7.5% real return on capital. As the table indicates, if the vessel catches only 150 tons per year, even at an average price of 60¢ per pound, the surplus is barely sufficient to generate a low-income living for owner and crew.

However, if the vessel is able to catch 300 tons per year, then the economic well-being of owner and crew is sharply dependent on price. An average landed price of 30¢ per pound will generate a low to moderate income of roughly \$12,000 to \$15,000 per head. But an average price of 40¢ per pound generates an income of over \$25,000 per head, and at 50¢ per pound, we are talking about average income of \$35,000 to \$40,000. Of course, if the vessel is fortunate enough to land more than 300 tons per year, the picture is still better.

In the last few years, Americans have been landing about 20,000 tons of yellowtail with roughly 8,000 days of effort. That is, they have been catching yellowtail at a rate of about 2.5 tons per day fished. At this rate, it is quite easy for an active vessel to catch 300-400 tons per year (which represents about one-third the vessel's potential capacity). Recent prices have certainly averaged better than 40¢ per pound. All of this would imply a per-capita income well in excess of \$25,000 for approximately 200 days at sea. In short, very good blue-collar income.

There are a number of factors which may make the above estimate conservative. The prices given are Boston large-lot averages. The freshest fish, caught the last day or two of the trip, can command a quality premium of 10¢ per pound or more. By custom, a portion of this premium fish is reserved to the crew for their own use. The resulting personal sales do not appear anywhere in NMFS statistics. In any event, while accurate documented estimates of true take-home income are by their nature hard to come by, the conventional picture of the struggling American fisherman working impossible hours for very low pay is simply not representative of the present situation facing the full-time Georges Bank fisherman.

And the basic reason is the increasingly inelastic character of the demand curve at low levels of landings. As we noted in Chapter 2, a drastically overfished situation with consequent low landings and high prices is not necessarily a bad thing for the fisherman, provided it can be maintained. We appear to have been in such a situation with respect to at least the yellowtail fishery over the last year or two. The other groundfish display the same phenomenon, although to a lesser degree. Herring, Figure 4.4.5, represents the other extreme of an almost perfectly elastic demand curve throughout. For this species, conventional fixed-price analysis appears appropriate.

In order to obtain demand curves from these scatter diagrams, a number of different functional forms were considered. These included linear, log-linear, linear-log, and log-log. For yellowtail, the best fit in terms of standard error was obtained by the following relationship:

$$p = 21.9 + 51.3/x$$

where p is the price in \$/kg and x is monthly landings in thousands of metric tons. The standard error for this fit was 12.6¢/kg. This fit is shown as the dashed line in Figure 4.4.1.

It is important to note that the choice of the demand curve form determines the elasticity behavior. Furthermore, the most commonly used forms, including the combinations of linear and log listed above, automatically imply that elasticity is constant or increases as price increases. If one uses such a form, not only does non-decreasing elasticity with lower landings occur, but one will generate a higher level of elasticity at the low end of landings and a lower level of elasticity at the high end, and end up proving that the demand for fish exhibits moderately high elasticity throughout. Unless a wide range of functional forms are examined, including functional forms which exhibit decreasing elasticity with increasing price, and the best fit is a constant or increasing elasticity form, then this proof is an artifact of the procedure and not of the data.

It turns out that surprisingly few simple functional forms exhibit decreasing elasticity with increasing price. The translated hyperbola shown above is one of those. However, this simple hyperbolic form does not actually turn inelastic until x goes to zero. Or to put it another way, at low landing levels this form exhibits nearly unitary elasticity. At these levels, the fisherman's revenue is essentially independent of how much he lands. As we obtain more price data on very low landings, we may find that we obtain a still better fit by going to a functional form which can turn inelastic. Such a form is the doubly translated hyperbola $p = a + b/(x - c)$.

4.5 Description of the RECRUIT routine

By far the most interesting of FISHDYN1's subroutines is RECRUIT. Once a year DRIVER calls this routine and its role is to return the new recruitment to the fishery for that year. As mentioned earlier, RECRUIT functions in one of three modes, each of which is described in the following three subsections.

4.5.1 Mode A: Exogenously fixed recruitment

In Mode A, recruitment is supplied exogenously by the user and is not a function of adult biomass. In this mode there is no stock-recruitment dependency. This mode can be used only for those species in which the user is willing to assume that recruitment is independent of the status of the spawning stock. In this mode, FISHDYN1 is functioning as a

classical growth overfishing model, ignoring the recruitment overfishing problem. In this mode, the model will generally go to steady state in five or six years, if effort is held constant. It is important to note that, except in the coincidental case that the stock is already at the steady-state equilibrium for this level of effort, the model has always taken at least two or three years to get to steady state. This should be very disconcerting to people who attempt to fit Schaefer models by using scatter diagrams of annual catch per unit effort versus effort.*

It is not our purpose here to review all the arguments against constant recruitment models. Rather, our purpose is to display the implications of assuming that stock and recruitment are related. Therefore, in our work, the principal use of Mode A was to show how differently a model in which recruitment is independent of stock behaves from a model in which this feedback is represented.

4.5.2 Mode B: Deterministic Ricker using least-squares estimates for parameters

Mode B assumes that recruitment is related to adult biomass according to the Ricker hypothesis. Ricker posited a relationship of the form:

*The need to hold effort constant at least one response time has been pointed out almost as often as it has been ignored. A model such as FISHDYN1 can be used to estimate the necessary response time.

A still more damaging argument against this procedure is that it will generate spurious correlations, even when catch and effort are completely independent since the inverse of effort is obviously negatively correlated with effort.

$$R = \alpha P e^{-\beta P}$$

Here R is recruitment in numbers, and P is the adult biomass in mass. In this paper, "recruitment" refers to the number of fish at first exploitable age. That is, if we are dealing with a fishery in which the fish first become exploited at age 3, then R represents the number of fish produced by the biomass which survives until age 3. This form is unimodal, that is, it assumes that there is one level of spawning biomass which will maximize recruitment and that as the biomass gets larger or smaller, recruitment will fall off monotonically. This modal level of biomass is $1/\beta$. α can be thought of as the number of surviving recruits per unit of spawning biomass when the spawning biomass is quite low.

The basic idea is that at very low adult biomass, the adults are healthy and at the same time not much of a threat to the larval and juvenile stages and hence recruits are produced and survive at some maximal rate per adult biomass, α . However, as the adult population grows, competition for food begins to affect adult fecundity, larval and juvenile growth, and the effect of cannibalism increases. If the biomass becomes large enough ($1/\beta$), a further increase in biomass will actually decrease the surviving number of recruits, and if infinite levels of biomass were somehow attained, the number of recruits would drop off to zero.

The Ricker form has a number of nice attributes. It goes to 0 at $P = 0$ and at $P = \infty$, properties that seem

appropriate in a recruitment function. The assumption of unimodality also seems reasonable, although one can concoct counterexamples. It also has some very nice statistical properties. Suppose we have observed in the past a time series of recruitment and adult biomass. Table 4.5.1 shows such data for the Georges Bank yellowtail taken from Parrack [1976]. Parrack used standard Virtual Population Analysis to derive population age distribution from catch data.* The yellowtail is a fish which is recruited late in its second year. If one assumes the primary effect of the adult biomass is in larvae's first year of life, then it makes sense to lag the adult biomass two or three years, i.e. we will assume that recruitment of two-year-olds in 1977 depends on adult biomass in 1975. The question, then, is how do we use Columns 2 and 3 of Table 4.5.1 to fit a Ricker recruitment relation.

An obvious approach is to make a logarithmic transformation of the data, suitably lagged, and then use classical regression techniques:

$$\log R_t = \log \alpha + \log P_{t-\tau} - \beta \log P_{t-\tau} + \epsilon_t \quad t = 1, \dots, T$$

τ is the lag, that is, the age at recruitment to the fishery.

ϵ_t is a random error variable, reflecting errors in our data and, more importantly, fluctuations due to variables outside

*Parrack's results are in terms of number of fish at each age. We converted Parrack's numbers for age group 2 through 10 to weight using the growth curve of Table 4.1.2.

TABLE 4.5.1
1963-1975 YELLOWTAIL STOCK AND RECRUITMENT DATA

Year	R_t Number of Two-Year-Old Fish Entering Fishery in Millions	P_t Adult Biomass in Thousands of Metric Tons
1963 ^a	54.2	30.2
1964 ^a	45.0	33.5
1965	41.8	27.7
1966	41.6	19.1
1967	67.1	19.6
1968	66.7	27.6
1969	65.7	32.9
1970	60.8	33.9
1971	52.0	29.9
1972	47.0	31.0
1973	35.1	27.9
1974	39.6	20.0 ^a
1975	45.3	14.7 ^a

^aCould not be used in regression due to two-year lag.
Biomass in 1961 and 1962 unknown as is recruitment in 1976 and 1977.

Source: Parrack [1976]. Adult population numbers converted to biomass by authors.

Note: Parrack numbers are unpublished and hence under continual revision. Recent work at National Marine Fisheries Service, Woods Hole (also unpublished) has indicated that the sampling process in use prior to 1974 was biased against small fish. More small fish were being landed than indicated in Parrack [1976]. This implies that recruitment (and young age group fishing mortality) may have been higher than Parrack estimated. NMFS Woods Hole is in the process of re-estimating all the yellowtail figures and a new set of estimates is expected to be published shortly.

the model (current, water temperature, other species' stock sizes, etc.) and T is the sample size. We will assume that the ϵ_t 's are independent zero-mean Normally distributed random variables with unknown variance. This assumption is necessary if we are to make use of all the statistical theory which has been developed for Normally distributed random fluctuations.

At this point, another nice feature of the Ricker form becomes apparent. In terms of untransformed variables, we are assuming that the variance of the random fluctuations is proportional to the size of the existing biomass. That is, in absolute terms we would expect to see larger fluctuations in recruitment when recruitment is high than when it is low. This seems reasonable--at least more reasonable than assuming the absolute fluctuations in recruitment are the same no matter what the expected level of recruitment is. More importantly, with proportional errors, we never see a negative recruitment, since the error is a fraction of the mean recruitment.*

In any event, having made the above choices, we apply classical regression theory to obtain that $\log \alpha$ and β which was most likely to have generated the observed sample. These estimates are computed by first computing the moment matrix N :

$$N = \begin{vmatrix} T & \sum \log P_{t-\tau} \\ \sum \log P_{t-\tau} & \sum (\log P_{t-\tau})^2 \end{vmatrix}$$

*The quadratic recruitment relationship explored by Doubleday [1976] does not have this property.

where T is the number of usable samples and each summation is from t equal 1 to T . This matrix is then inverted, obtaining $NINV$. The least-square estimates are then obtained:

$$\log \hat{\alpha} = \sum_{t=1}^T [(NINV(1,1) + NINV(1,2) \log P_{t-\tau}) [\log R_t - \log P_{t-\tau}]]$$

$$\hat{\beta} = \sum_{t=1}^T [(NINV(2,1) + NINV(2,2) * \log P_{t-\tau}) [\log R_t - \log P_{t-\tau}]]$$

Note the central role played by the inverse of the moment matrix in these computations.

These computations are carried out by the computer program RICKER which takes as input $(R_t, P_{t-\tau})$ $t = 1, 2, \dots, T$ and outputs, among other things, the Maximum Likelihood Estimates for $\log \alpha$ and β as well as the inverse of the moment matrix.

Figure 4.5.1 shows the results of applying RICKER to Parrack's yellowtail stock recruitment data for the period 1963 to 1975. A scatter diagram of the data is included on the figure. According to this data and this analysis, maximal recruitment will occur at an adult biomass of about 14,000 tons, at which point recruitment (two years later) will be sixty-eight million fish.

It is obvious that the Ricker-form hypothesis is a rather heroic assumption, for we have yet to observe recruitment of adult stock levels at and below the peak. Unfortunately,

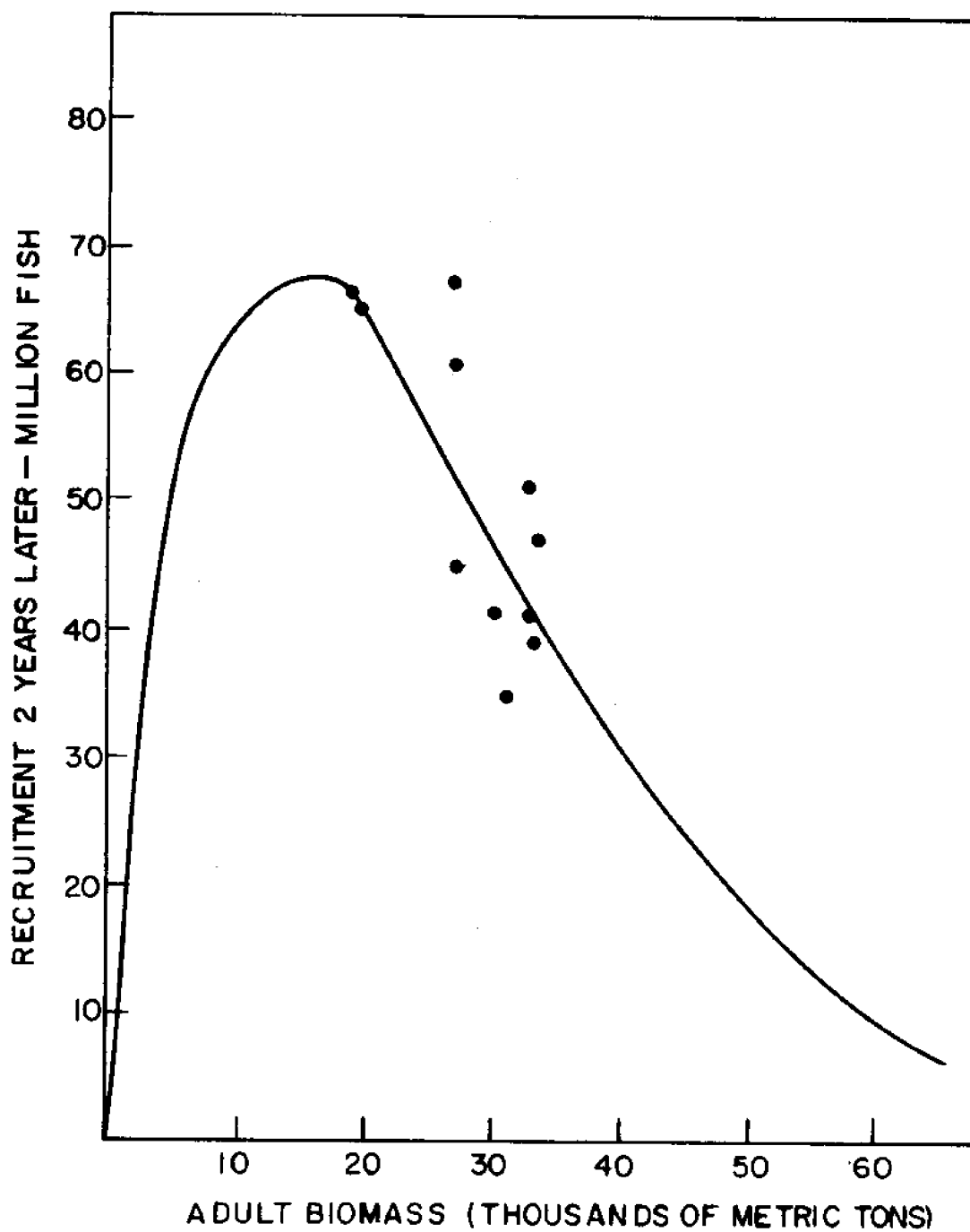


FIGURE 4.5.1 RICKER RECRUITMENT CURVE FOR YELLOWTAIL
LOGARTHMIC LEAST SQUARES FIT TO 1963 -
1975 DATA WITH TWO YEAR LAG

we may remedy this deficiency in a year or two. But the same basic problems of a rather narrow band of recruitment observations confronts any choice of functional form (including the assumption of constant recruitment--an assumption which is almost certainly wrong, at least at extremely low and high levels of stock).

The position of the peak (also known as the mode) in the recruitment curve is an extremely important determinant of the dynamic behavior of the fishery. If the adult stock is to the right of this level, then the situation tends to be much more stable than if the stock level is to the left of the peak. To the right of the mode, a decrease in stock size increases recruitment and conversely an increase decreases recruitment. Hence, above the mode, any perturbation in stock size sets in motion a restoring variation in recruitment. Of course, this adjusted recruitment does not join the adult stock for several years, so the adult stock fluctuation may be damped rather slowly. But still the inherent long-run stability of the system is apparent.

If, however, the adult stock drops below the peak, then we are in a quite different situation. A further decrease in stock decreases recruitment and vice versa. In short, below the modal stock level, any stock variation is inherently unstable. This does not necessarily mean that the fishery must be wiped out. At extremely low stock levels, even very low recruitment can generate a biomass which at recruitment is larger than the adult stock which spawned that recruitment. But it does mean we are on a roller coaster. Once adult stock drops below the mode, it will keep

dropping by itself until this phenomenon occurs, whereupon a rebound all the way back up to the mode will occur, assuming no fishing effort and that adult natural mortality is not density-dependent. Continued fishing effort in this situation will force the stock to remain at extremely low levels or wipe it out, depending on whether or not the new recruits get a chance to spawn before they are fished. Clearly, a basic tenet of intelligent fisheries management is to keep the adult stock at levels to the right of the peak in the recruitment curve.

The crucial importance of the position of the peak of the stock-recruitment curve exposes a basic flaw in the Ricker form hypothesis. As mentioned earlier, the mode occurs at β^{-1} . Hence, the parameter β determines the position of the peak. Unfortunately, β also completely determines the shape of the recruitment curve. α is merely a linear scaling factor. In the Ricker form, it is impossible to have a mode near zero without a very short tail or a mode well above zero without a long tail. To put it another way, Ricker-form curves with modes near zero are necessarily very narrow with recruitment dropping off extremely rapidly at high levels of stocks. Ricker-form curves with modes well away from zero are necessarily very spread out with recruitment dropping off very slowly at high stock levels. We are informing Nature that she simply cannot have a species which is inherently stable (peak near zero) but which can also support substantial recruitment at stock levels several times or more the modal level. Similarly, we are informing her there is no such thing as a highly tuned species--mode well above zero but supporting substantial recruitment only over a narrow range of stock.

The authors see no justification for this arrogance.

An obvious generalization of the Ricker form is:

$$R = \alpha P^\gamma e^{-\beta P} \quad \gamma > 0$$

This form, the unnormalized Gamma density, is unimodal, and has the same behavior as the Ricker at 0 and ∞ , but allows Nature complete freedom to position the mode and determine the spread-outness of the recruitment relationship independently. Like the Ricker, by taking logs the relationship becomes linear in the three unknown coefficients (α, β, γ) and ordinarily multivariate regression analysis can be used. Since the Ricker form is a special case, if it is in fact true, the data will begin to reveal this fact by pointing to a γ near 1. If, on the other hand, recruitment is in fact nearly independent of stock, as some claim, then the data should come up with a near-zero γ .^{*} This form is general enough so just about any unimodal stock-recruitment curve which goes to zero at zero stock and infinite stock levels can be approximated reasonably well by a member of this three-parameter family. One can have widely spread out curves with near-zero peaks and very narrow curves with peak well above zero. Hence, in using this more general form, the analyst is not really assuming anything more than unimodality and zero recruitment at the end points.

We strongly recommend that future stock-recruitment studies use the Gamma form. Unfortunately, we have not

^{*}And a near-zero β . α in this situation will tend to the unknown, fixed level of recruitment. The unnormalized Gamma has the strange ability to be very nearly constant from 0+ to ∞ and still drop to zero when P equals 0, which is another argument for its use.

followed this excellent piece of advice and all the stock-recruitment work in this report is based on the Ricker form.

4.5.3 Mode C: Monte Carlo sampling from posterior recruitment densities obtained by Bayesian regression of data

In Mode B, we took a classical view of the problem of fitting a recruitment curve to the available data. The aim was to obtain those estimates of the parameters α and β which minimize the sum of the squared errors (after logarithmic transformation). This set of least-square estimators, $\hat{\alpha} = \exp(\log \hat{\alpha})$ and $\hat{\beta}$, is also the values of the parameters which were most likely to produce the data under the above assumptions. However, the probability that $\hat{\alpha}$ and $\hat{\beta}$ so derived actually equal the true value of α and β is in general vanishingly small. $\hat{\alpha}$ and $\hat{\beta}$ may be the best estimators in the logarithmic least-squares sense but still may not be very good in the sense that there remains a good chance that the data was generated by an α and β significantly different from these estimates.

The Bayesian approach to this problem of our uncertainty about α and β even after we have observed the data is rather different in philosophy from the classical. The Bayesian regards the true values of α and β as random variables about which we can never be sure and attempts to develop probability densities--not point estimates--of these random variables from the data. If he makes the same assumptions about

independent, zero-mean, Normally distributed errors with unknown variance and if before he observes the sample of stock-recruitment data he assumes he has absolutely no knowledge about α and β ,* then one can show by application of the basic rules of probability and considerable algebra that the posterior probability density on $\log \alpha$, β , and σ the unknown error variance after having observed the data,

$$p(\log \alpha, \beta, \sigma | (R_t, P_{t-\tau}), t=1, 2, \dots, T)$$

is proportional to

$$\frac{1}{\sigma^{T+1}} \exp \left\{ -\frac{1}{2\sigma^2} [(T-2)s^2 + (\log \alpha - \log \hat{\alpha}, \beta - \hat{\beta}) \cdot N \cdot (\log \alpha - \log \hat{\alpha}, \beta - \hat{\beta})'] \right\}$$

where N is the Moment Matrix; $\log \hat{\alpha}$, $\hat{\beta}$ are the least-square estimators of $\log \alpha$ and β respectively; and s^2 is the sample variance after the logarithmic transformation

$$s^2 = \frac{1}{T-2} \sum_{t=1}^T (\log R_t - (\log \hat{\alpha} + \hat{\beta} P_{t-\tau}))^2$$

Conditional on σ , the unknown variance of the random fluctuations in recruitment, $\log \alpha$ and β are distributed Normally with means equal to $\log \hat{\alpha}$ and $\hat{\beta}$ and covariance matrix equal to $N \text{INV} \cdot \sigma^2$.** Although this is mildly

*In the Bayesian jargon, the prior on α, β , and the unknown error variance σ before observing any data used is Jeffrey's non-informative conjugate prior, $1/\sigma$.

**If all the observations of recruitment are based on a narrow range of adult biomass, the elements of $N \text{INV}$ will tend to be very large. Thus, the fact that our observations on recruitment are not spread out over the entire range of adult biomass increases our uncertainty on α and β , as it should.

interesting, it's of little use in practice since we don't know σ . In fact, our uncertainty about σ reflects our uncertainty as to the size of the random fluctuations in recruitment being generated by all elements outside the model: hydrographic conditions, other stock sizes, etc. One can get rid of the troublesome parameter σ by integrating it out. This will result in a bivariate Student density in $\log \alpha$ and β . Perhaps, more interestingly, if one integrates out $\log \alpha$ and β , one finds that σ is distributed according to an inverted Gamma whose variance depends on the simple variance

$$p(\sigma | (R_t, P_{t-\tau}), t=1, 2, \dots, T) = \frac{1}{\sigma^{T-1}} \exp \left(- \frac{(T-2)s^2}{2\sigma^2} \right)$$

So the analysis allows us to be quantitative about our uncertainty as to the size of the random fluctuations in recruitment.

Of course, our real goal is not a density on σ , or even densities on the unknown parameters of the Ricker form, α and β . After all, α and β are only means to an end. That end is a density on future recruitment given the current adult biomass. However, this set of densities can be obtained from the density on the Ricker-form parameters and σ by employing some elementary probability and some rather tedious algebra. Let R_{T+1} be the yet unknown recruitment which will occur τ years from now and let $P_{T+1-\tau}$ be the current biomass, the biomass upon which R_{T+1} depends. From basic probability, we have

Log of Future Recruitment Per Biomass	Present Adult Biomass	Past Stock Recruitment Data
---	-----------------------------	--------------------------------

$$p[\log(R_{T+1}/P_{T+1-\tau}) | P_{T+1-\tau}, (R_t, P_{t-\tau}), t=1, 2, \dots, T] \text{ equals}$$

$$\int \int \int p(\log R_{T+1} | P_{T+1-\tau}, \log \alpha, \beta, \sigma) p(\log \alpha, \beta, \sigma | (R_t, P_{t-\tau}), t=1, T) \\ \log \alpha \quad \beta \quad \sigma$$

The first term within the integral is the single-sample likelihood function. The second term is the posterior density on $(\log \alpha, \beta, \sigma)$ given the past data--the density on the page before last.

Substituting in these densities and performing the required integrations, one eventually finds that

$p[\log(R_{T+1}/P_{T+1-\tau}) | P_{T+1-\tau}, (R_t, P_{t-\tau}), t=1, 2, \dots, T]$ is proportional to

$$(T-2) + (\log R_{T+1} - [\log \hat{\alpha} + \hat{\beta} \cdot P_{T+1-\tau}])^2 \cdot \frac{1}{s^2} (1 - [1, P_{T+1-\tau}] \cdot \text{NAUG}^{-1} \cdot [1, P_{T+1-\tau}]')$$

where NAUG^{-1} is the inverse of the augmented moment matrix

$$\text{NAUG} = N + \begin{bmatrix} 1 & \log P_{T+1-\tau} \\ \log P_{T+1-\tau} & (\log P_{T+1-\tau})^2 \end{bmatrix}$$

NAUG is just the moment matrix for all observations of biomass including the current biomass.*

*See Zellner [1971], pages 62 through 75, for the complete argument. The apostrophes in the above expressions denote the vector transpose operation. Thus, in the expression for the probability density of $\log R_{T+1}$, the matrix NAUG^{-1} is premultiplied by the row vector $(1, P_{T+1-\tau})$ and postmultiplied by its transpose, the column vector with the same elements.

Despite its long-winded form, the above density is merely a univariate student density whose mean is

$$\text{mean}(\log R_{T+1} | P_{T+1-\tau}) = \log \hat{\alpha} + \hat{\beta} P_{T+1-\tau} + \log P_{T+1-\tau}$$

and whose variance is

$$\text{VAR}(\log R_{T+1} | P_{T+1-\tau}) = \frac{(T-2)s^2}{(T-4)} (1 + (1, \log P_{T+1-\tau}) \cdot \text{NINV} \cdot (1, \log P_{T+1-\tau})')$$

However, it's important to note that what we have developed is a family of densities for future recruitment conditioned on the current adult biomass. In order to evaluate the probability of various recruitments τ years from now, one must know the current adult biomass. Recruitment still depends on current biomass but now the dependence is stochastic in nature. Biomass affects the probabilities of future recruitment. It does not determine future recruitment. In fact, the mean of the log of future recruitment is the straightforward Ricker curve whose parameters are the least-square estimators of $\log \hat{\alpha}$ and $\hat{\beta}$.

The above density is still in terms of the logarithm of future recruitment. However, a simple little antilog transformation brings us back to future recruitment proper. Performing the transformation, we find that $p(R_{T+1} | P_{T+1-\tau})$ equals

$$\left(\frac{h}{\pi}\right)^{\frac{1}{2}} \frac{\Gamma\left[\frac{(T-1)}{2}\right] \Gamma\left[\frac{(T-2)}{2}\right]}{\Gamma\left[\frac{(T-2)}{2}\right] R_{T+1}} \left[(T-2) + \frac{h}{s^2} \cdot [\log(R_{T+1}/P_{T+1-\tau}) - (\log \hat{\alpha} + \hat{\beta} \cdot P_{T+1-\tau})] \right]^{\frac{(T-1)}{2}}$$

where

$$h = 1 - (1, P_{T+1-\tau}) \cdot \text{NAUG}^{-1} \cdot (1, P_{T+1-\tau})'$$

and

Γ denotes the complete Gamma integral.

This transformation results in a log-student density which has the desirable property that recruitment cannot take on negative values. However, being an unsymmetrical density--a highly unsymmetric density of the ratio of its standard deviation to its mean is not small--one must guard against attributing Normal-like properties to it. For example, the most likely recruitment will always be less than the mean recruitment for a given adult biomass--sometimes considerably less.

Note that in order to compute the recruitment density for any given current adult biomass, one needs the least square estimates $\log \hat{\alpha}$ and $\hat{\beta}$, the number of samples, T , the sample variance, s^2 , and the inverse of the moment matrix, NINV .

The program RICKER computes all these statistics so that they may be transferred to the appropriate Species Data File (see Section 4.1).

The user of FISHDYN1 is spared all the algebra inherent in the above expression. He merely inputs the past stock-recruitment data to RICKER.

RICKER also computes this density for a range of stock sizes. Table 4.5.2 shows typical output from a run of RICKER. The particular run shown is that for yellowtail flounder based on Parrack's 1963 to 1975 data lagged two years. The program first prompts for the number of samples and then the stock-recruitment data. The adult population P is entered in millions of age 2 fish. The program then prints out the logarithmic least-square estimators, the logarithmic sample variance, and the transformed estimators. In the output, the untransformed estimates $\log \hat{\alpha}$ and $\hat{\beta}$ are called $B(1)$ and $B(2)$ respectively, the transformed estimates $\hat{\alpha}$ and $\hat{\beta}$ are called A and B respectively, and the variance of the logarithmic sample is called $SSQRD$. The program then prints out the moment matrix ($NMATRIX$) and its inverse ($NINVERSE$).

The next set of output displays various parameters of the log of future recruitment (called Y) density as a function of present adult biomass (called X and shown in thousands of metric tons). Information shown includes the mean, the variance, the value of the density at its peak, which will be when Y equals the mean of Y . The program also outputs the regression line $\log \hat{\alpha} + \hat{\beta}X$ as a function of X as well as the position of the peak of the density on future recruitment

EXEC GORICKER

ENTER CHANGES TO CONTROL OPTIONS: ;

ENTER NUMBER OF SAMPLES: 11

ENTER SAMPLE PAIRS; FIRST P, THEN R.

```

: 20.193 41.730
: 33.476 41.640
: 27.699 67.072
: 19.016 66.637
: 19.502 65.565
: 27.535 60.758
: 22.861 51.966
: 13.926 47.003
: 23.920 39.365
: 30.975 39.600
: 27.639 46.500

```

MAXIMUM LIKELIHOOD ESTIMATORS ARE:

```

B(1)= 2.5794056E+00
B(2)= 7.0320156E-02
S(2)= 1.3292420E-02

```

TRANSFORMED KLE ESTIMATORS ARE:

```

A= 1.3189295E+01
B= -7.0320156E-02

```

NMATRIX(1,1)= 1.100000000000000E+01

NINVERSE(1,1)= 9.16756493699395E+03

NINVERSE(2,2)= -1.118467575037091E-01

LOGFACT= 1.003946291431849E+01

NMATRIX(1,2)= 3.13120999999999E+02

NINVERSE(1,1)= 3.274688050577263E+00

NINVERSE(2,2)= 3.929197762340724E-03

LGAM1= 2.453736570842442E+00

NMATRIX(2,1)= 3.13120999999999E+02

NINVERSE(1,2)= -1.118467575037091E-01

LGAM2= 3.178053830347945E+00;

TABLE 4.5.2

Sample Run of Program RICKER
Yellowtail Recruitment Based
on Parack 63-75 Data

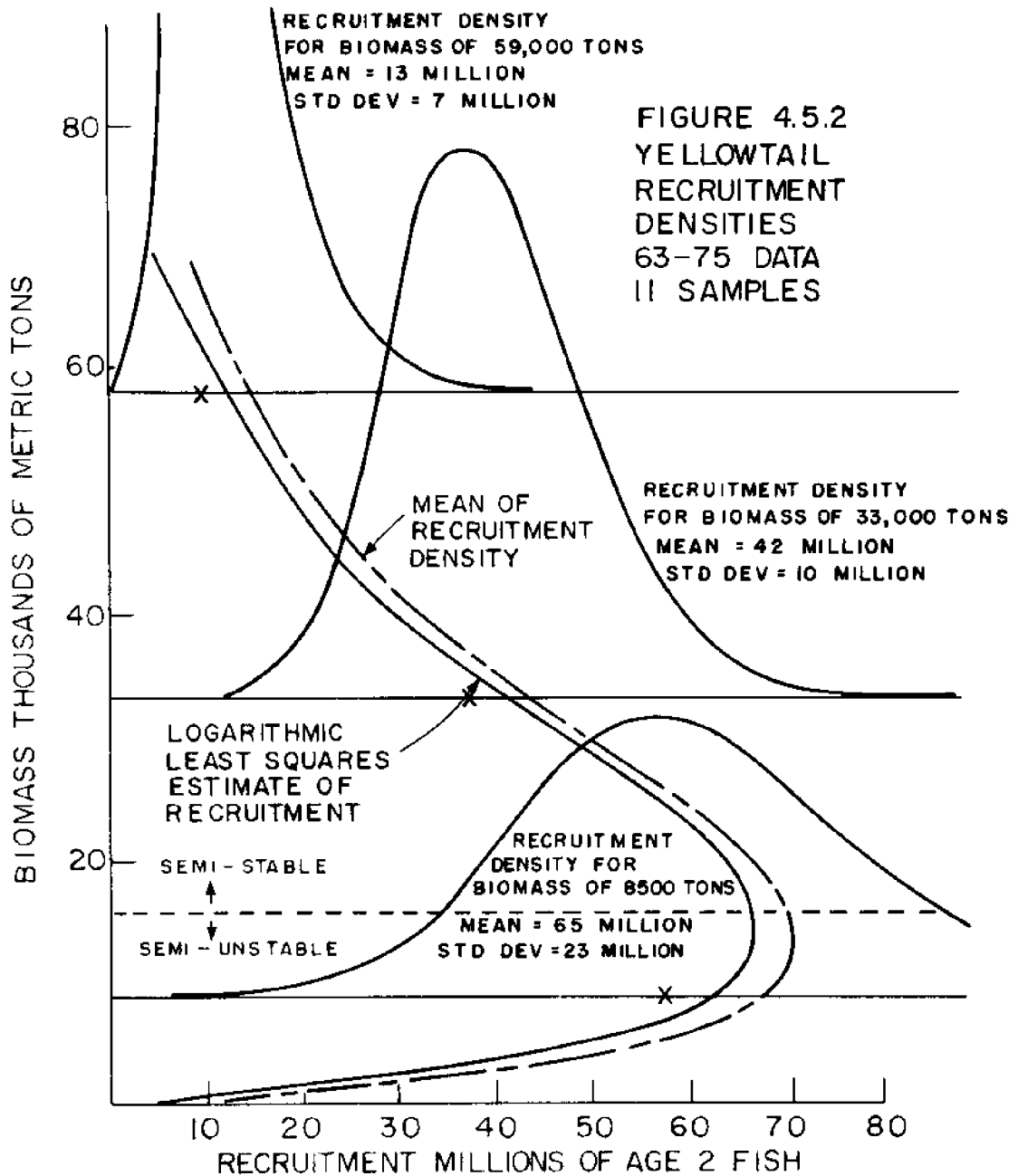
BASED ON GIVEN SAMPLE, NEXT Y IS STUDENT DISTRIBUTED WHOSE PARAMETERS
AS A FUNCTION OF X ARE GIVEN BELOW. THE DEGREE OF FREEDOM IS 9

X	MEAN OF Y	VAR. OF Y	PREC. OF Y	MAX DENS OF Y	Y REGRESSION LINE	MODE OF R	MAX DENS OF R
6.7257000E-01	2.5316919E+00	1.7655665E-01	7.2821631E+00	1.0471105E+00	8.5222237E+00	7.5284304E+00	1.3080014E-01
9.4819300E+00	1.2929352E+00	1.1284361E-01	1.1291705E+01	1.3099189E+00	6.1612975E+01	5.6856023E+01	2.207010E-02
1.6361300E+01	1.3355649E+00	6.8949528E-02	1.9647451E+01	1.6756393E+00	6.7670345E+01	6.4657339E+01	2.5293343E-02
2.5444500E+01	7.5014435E-01	4.6233876E-02	2.6657494E+01	2.0034593E+00	5.6012411E+01	5.4204692E+01	3.6339159E-02
3.5926000E+01	1.3372393E-01	5.1710651E-02	2.4863628E+01	1.9348755E+00	4.1178062E+01	3.9706334E+01	4.7897750E-02
4.2407500E+01	4.0269645E-01	7.9387853E-02	1.6195353E+01	1.5615564E+00	2.8350055E+01	2.6809197E+01	5.6638625E-02
5.0889000E+01	9.9911683E-01	1.3182488E-01	9.7949363E+00	1.2144307E+00	1.8737555E+01	1.7077914E+01	6.7874221E-02
5.9270500E+01	-1.1595537E+00	2.0733454E-01	6.2011583E+00	9.6628933E-01	1.2040310E+01	1.0391166E+01	8.6341256E-02
6.7852600E+01	-2.1919577E+00	3.0750402E-01	4.1797703E+00	7.9531749E-01	7.5789230E+00	6.0811930E+00	1.1611775E-01

R	LOG-STUDENT DENSITY OF NEXT R FOR EIGHT DIFFERENT P	LOG-STUDENT DENSITY OF NEXT R FOR EIGHT DIFFERENT P	LOG-STUDENT DENSITY OF NEXT R FOR EIGHT DIFFERENT P
0.16763	0.67852	3.48150	16.96300
1.39555E-05	4.2294E-03	4.02744E-09	1.13221E-09
4.08266E-05	7.2970E-08	6.74716E-09	1.98771E-09
0.50720	1.06620E-07	9.20499E-09	2.97158E-09
0.87072	1.65874E-04	1.45004E-07	1.32803E-03
0.83440	1.89653E-07	1.72490E-08	5.59420E-09
1.00660	2.38032E-07	2.17492E-08	7.13656E-09
1.11376	2.93523E-07	2.67812E-08	8.98473E-09
1.31744	3.55278E-07	3.24919E-08	1.13631E-08
1.50912	4.25294E-07	3.95302E-08	1.3451E-08
1.67680	4.94862E-04	4.56329E-08	1.61410E-08
1.83443	5.87622E-07	5.3421E-08	1.91791E-08
2.01316	6.81735E-07	6.19400E-08	2.2898E-08
2.17944	7.85152E-07	7.13650E-08	2.61055E-08
2.34752	8.92548E-07	8.16342E-08	3.06610E-08
2.51520	1.02257E-06	9.29435E-08	3.53936E-08
2.68288	1.15790E-06	1.0531E-07	4.0430E-08
2.85056	1.23012E-03	1.18795E-07	4.64515E-07
3.01824	1.30105E-02	1.33477E-07	5.29255E-07
3.18592	1.36955E-05	1.49060E-07	5.9906E-07
3.35360	1.43547E-03	1.65410E-08	6.74076E-08
3.52128	1.49953E-03	1.82418E-08	7.54747E-08
3.68896	1.56155E-03	2.00051E-08	8.41465E-08
3.85664	1.62155E-03	2.18353E-08	9.34241E-08
4.02432	1.67955E-03	2.37375E-08	1.03433E-07
4.19200	1.73555E-03	2.57145E-08	1.14195E-07
4.35968	1.78955E-03	2.77705E-08	1.25735E-07
4.52736	1.84155E-03	2.98995E-08	1.38125E-07
4.69504	1.89155E-03	3.20995E-08	1.51395E-07
4.86272	1.93955E-03	3.43695E-08	1.65695E-07
5.03040	1.98555E-03	3.67095E-08	1.81095E-07
5.19808	2.02955E-03	3.91195E-08	1.97595E-07
5.36576	2.07155E-03	4.15995E-08	2.15195E-07
5.53344	2.11155E-03	4.41495E-08	2.33895E-07
5.70112	2.14955E-03	4.67695E-08	2.53695E-07
5.86880	2.18555E-03	4.94595E-08	2.74695E-07
6.03648	2.21955E-03	5.22195E-08	2.96895E-07
6.20416	2.25155E-03	5.50495E-08	3.20295E-07
6.37184	2.28155E-03	5.79495E-08	3.44895E-07
6.53952	2.30955E-03	6.09195E-08	3.70695E-07
6.70720	2.33555E-03	6.39595E-08	3.97695E-07
6.87488	2.35955E-03	6.70695E-08	4.25895E-07
7.04256	2.38155E-03	7.02495E-08	4.55295E-07
7.21024	2.40155E-03	7.34895E-08	4.85895E-07
7.37792	2.41955E-03	7.67895E-08	5.17695E-07
7.54560	2.43555E-03	8.01495E-08	5.50695E-07
7.71328	2.44955E-03	8.35695E-08	5.84895E-07
7.88096	2.46155E-03	8.70495E-08	6.20295E-07
8.04864	2.47155E-03	9.05895E-08	6.56895E-07
8.21632	2.47955E-03	9.41895E-08	6.94695E-07
8.38400	2.48555E-03	9.78495E-08	7.33695E-07
8.55168	2.48955E-03	1.01569E-07	7.73895E-07
8.71936	2.49155E-03	1.05249E-07	8.15295E-07
8.88704	2.49255E-03	1.08489E-07	8.57895E-07
9.05472	2.49255E-03	1.11289E-07	9.01695E-07
9.22240	2.49155E-03	1.13649E-07	9.46695E-07
9.39008	2.48955E-03	1.15569E-07	9.92895E-07
9.55776	2.48655E-03	1.17049E-07	1.04029E-06
9.72544	2.48255E-03	1.18089E-07	1.08869E-06
9.89312	2.47755E-03	1.18689E-07	1.13809E-06
10.06080	2.47155E-03	1.18849E-07	1.18849E-06
10.22848	2.46455E-03	1.18569E-07	1.23989E-06
10.39616	2.45655E-03	1.17849E-07	1.29229E-06
10.56384	2.44755E-03	1.16689E-07	1.34569E-06
10.73152	2.43755E-03	1.15089E-07	1.40009E-06
10.89920	2.42655E-03	1.13049E-07	1.45549E-06
11.06688	2.41455E-03	1.10569E-07	1.51189E-06
11.23456	2.40155E-03	1.07649E-07	1.56929E-06
11.40224	2.38755E-03	1.04289E-07	1.62769E-06
11.56992	2.37255E-03	1.00489E-07	1.68709E-06
11.73760	2.35655E-03	9.6249E-08	1.74749E-06
11.90528	2.33955E-03	9.1649E-08	1.80889E-06
12.07296	2.32155E-03	8.6649E-08	1.87129E-06
12.24064	2.30255E-03	8.1249E-08	1.93469E-06
12.40832	2.28255E-03	7.5449E-08	1.99909E-06
12.57600	2.26155E-03	6.9249E-08	2.06449E-06
12.74368	2.23955E-03	6.2649E-08	2.13089E-06
12.91136	2.21655E-03	5.5649E-08	2.19829E-06
13.07904	2.19255E-03	4.8249E-08	2.26669E-06
13.24672	2.16755E-03	4.0449E-08	2.33609E-06
13.41440	2.14155E-03	3.2249E-08	2.40649E-06
13.58208	2.11455E-03	2.3649E-08	2.47789E-06
13.74976	2.08655E-03	1.4649E-08	2.54929E-06
13.91744	2.05755E-03	5.2449E-09	2.62169E-06
14.08512	2.02755E-03	3.3949E-09	2.69509E-06
14.25280	1.99655E-03	1.5149E-09	2.76949E-06
14.42048	1.96455E-03	5.1449E-10	2.84489E-06
14.58816	1.93155E-03	1.1449E-10	2.92129E-06
14.75584	1.89755E-03	2.2449E-11	2.99869E-06
14.92352	1.86255E-03	3.6449E-12	3.07709E-06
15.09120	1.82655E-03	5.2449E-13	3.15649E-06
15.25888	1.78955E-03	7.0449E-14	3.23689E-06
15.42656	1.75155E-03	9.0449E-15	3.31829E-06
15.59424	1.71255E-03	1.1249E-14	3.39969E-06
15.76192	1.67255E-03	1.3649E-15	3.48109E-06
15.92960	1.63155E-03	1.6249E-16	3.56349E-06
16.09728	1.58955E-03	1.9049E-17	3.64689E-06
16.26496	1.54655E-03	2.2149E-18	3.73129E-06
16.43264	1.50255E-03	2.6549E-19	3.81669E-06
16.60032	1.45755E-03	3.2349E-20	3.90309E-06
16.76800	1.41155E-03	3.9549E-21	3.99049E-06
16.93568	1.36455E-03	4.8249E-22	4.07889E-06
17.10336	1.31655E-03	5.8549E-23	4.16829E-06
17.27104	1.26755E-03	7.0549E-24	4.25869E-06
17.43872	1.21755E-03	8.4349E-25	4.35009E-06
17.60640	1.16655E-03	9.9949E-26	4.44249E-06
17.77408	1.11455E-03	1.1849E-26	4.53589E-06
17.94176	1.06155E-03	1.4049E-27	4.63029E-06
18.10944	1.00755E-03	1.6649E-28	4.72569E-06
18.27712	9.5255E-04	1.9749E-29	4.82209E-06
18.44480	8.9655E-04	2.3349E-30	4.91949E-06
18.61248	8.3955E-04	2.7549E-31	5.01789E-06
18.78016	7.8155E-04	3.2349E-32	5.11729E-06
18.94784	7.2255E-04	3.7749E-33	5.21769E-06
19.11552	6.6255E-04	4.3849E-34	5.31909E-06
19.28320	6.0155E-04	5.0649E-35	5.42149E-06
19.45088	5.3955E-04	5.8249E-36	5.52489E-06
19.61856	4.7655E-04	6.6649E-37	5.62929E-06
19.78624	4.1255E-04	7.6849E-38	5.73469E-06
19.95392	3.4755E-04	8.9949E-39	5.84109E-06
20.12160	2.8155E-04	1.0649E-39	5.94849E-06
20.28928	2.1455E-04	1.2649E-40	6.05689E-06
20.45696	1.4655E-04	1.5049E-41	6.16629E-06
20.62464	8.6555E-05	1.7849E-42	6.27669E-06
20.79232	5.0555E-05	2.1149E-43	6.38809E-06
20.96000	2.9555E-05	2.5049E-44	6.49949E-06
21.12768	1.6555E-05	2.9549E-45	6.61189E-06
21.29536	9.2555E-06	3.4749E-46	6.72529E-06
21.46304	5.2555E-06	4.0749E-47	6.83969E-06
21.63072	2.9555E-06	4.7649E-48	6.95509E-06
21.79840	1.6555E-06	5.5549E-49	7.07149E-06
21.96608	9.2555E-07	6.4549E-50	7.18889E-06
22.13376	5.2555E-07	7.4749E-51	7.30729E-06
22.30144	2.9555E-07	8.6249E-52	7.42669E-06
22.46912	1.6555E-07	9.9149E-53	7.54709E-06
22.63680	9.2555E-08	1.13549E-53	7.66849E-06
22.80448	5.2555E-08	1.29949E-54	7.79089E-06
22.97216	2.9555E-08	1.48649E-55	7.91429E-06
23.13984	1.6555E-08	1.69849E-56	8.03869E-06
23.30752	9.2555E-09	1.93649E-57	8.16409E-06
23.47520	5.2555E-09	2.20149E-58	8.29049E-06
23.64288	2.9555E-09	2.59449E-59	8.41789E-06
23.81056	1.6555E-09	3.02649E-60	8.54629E-06
23.97824	9.2555E-10	3.50849E-61	8.67569E-06

3.15592	1.61356E-02	1.59002E-06	1.493365E-07	5.99326E-08	2.39337E-07	5.01726E-06	2.26844E-04	5.6512E-03
3.45634	3.6671E-02	2.43014E-06	2.27384E-07	9.18624E-09	4.11143E-07	1.1266E-05	4.42363E-04	1.03063E-02
3.52735	5.6671E-02	3.62824E-06	2.29411E-07	9.18624E-09	6.74707E-07	1.97224E-05	8.04793E-04	3.0730E-02
5.12603	1.13942E-02	5.11927E-06	4.73219E-07	2.18475E-07	1.06939E-06	3.32761E-05	1.38355E-03	2.56435E-02
5.33393	1.0426E-01	7.05352E-06	6.59226E-07	3.16732E-07	1.84903E-06	5.46474E-05	2.26599E-03	2.59390E-02
6.15552	1.2821E-01	9.5333E-06	8.94356E-07	4.49975E-07	2.48630E-06	8.70451E-05	3.55471E-03	4.71333E-02
7.21024	1.29364E-01	1.26731E-05	1.19375E-06	6.28599E-07	3.56119E-06	1.35403E-04	5.36135E-03	5.82934E-02
7.31095	1.29364E-01	1.69362E-05	1.58451E-06	8.16571E-07	5.36849E-06	2.06299E-04	7.79459E-03	6.64170E-02
7.51613	1.22345E-01	2.11611E-05	2.07014E-06	1.17780E-06	7.71210E-06	3.08450E-04	1.09449E-02	7.66599E-02
9.22240	1.10303E-01	2.71461E-05	2.67576E-06	1.59545E-06	1.09563E-06	4.5312E-04	1.48654E-02	8.24944E-02
9.23212	3.69449E-02	3.47591E-05	4.42995E-06	2.11436E-06	1.54029E-05	6.55579E-04	1.95554E-02	8.56650E-02
10.56534	8.2933E-02	4.38280E-05	4.25939E-06	2.79547E-06	2.14511E-05	9.3362E-04	2.49421E-02	6.6266E-02
13.91744	3.10477E-02	1.21896E-04	1.12505E-05	1.02607E-05	1.00169E-04	4.40342E-03	5.51141E-02	6.46199E-02
17.27104	1.1794E-02	2.95366E-04	3.50310E-05	3.3323E-05	4.00515E-04	1.4502E-02	6.7282E-02	3.6418E-02
20.62464	4.0770E-03	6.43966E-04	8.56158E-05	9.9397E-05	1.39313E-03	3.2797E-02	5.67139E-02	1.88593E-03
23.37324	1.9413E-03	1.2767E-03	1.94680E-04	2.74929E-05	4.17855E-03	5.0911E-02	3.6760E-02	9.79435E-03
27.33184	9.4551E-04	2.3143E-03	4.16304E-04	7.0785E-04	1.05242E-02	5.6451E-02	2.1604E-02	5.2734E-03
33.93634	6.01697E-04	3.91231E-03	8.38157E-04	1.6912E-03	2.15972E-02	4.8115E-02	1.2227E-02	2.9743E-03
34.01904	2.86297E-04	6.14963E-03	1.59049E-03	3.71123E-03	3.52711E-02	3.4251E-02	6.9289E-03	1.7561E-02
37.33234	1.7251E-04	8.9121E-03	2.63972E-03	7.53936E-03	4.5571E-02	2.1833E-02	4.0846E-03	1.0863E-02
40.74024	1.2126E-04	1.21094E-02	7.7563E-03	1.31443E-02	4.74132E-02	1.3244E-02	2.3876E-03	6.9313E-04
44.99934	7.2557E-05	1.53255E-02	7.45201E-03	2.0643E-02	4.1134E-02	7.8596E-03	1.4682E-03	4.6471E-04
47.43344	4.93490E-05	1.82280E-02	1.08369E-02	2.84034E-02	3.1111E-02	4.6738E-03	3.9199E-04	3.1911E-04
50.80734	3.5255E-05	2.04319E-02	1.48054E-02	3.4213E-02	2.1419E-02	8.1951E-03	6.0967E-04	2.2524E-04
52.15084	2.5045E-05	2.17147E-02	1.87376E-02	3.6338E-02	1.3917E-02	1.7365E-03	4.1013E-04	1.6291E-04
57.51424	2.9026E-05	2.20391E-02	2.1028E-02	3.4505E-02	8.7729E-03	1.0951E-03	2.8309E-04	1.2041E-04
60.92744	1.4425E-05	2.14022E-02	2.43930E-02	2.9520E-02	5.4687E-03	7.0764E-04	1.9397E-04	9.0733E-05
64.12344	1.1134E-05	2.0039E-02	2.5281E-02	2.3921E-02	3.1149E-03	4.6837E-04	1.4432E-04	6.9558E-05
67.57504	8.7159E-06	1.82955E-02	2.47918E-02	1.81495E-02	2.1534E-03	3.1721E-04	1.0617E-04	5.4159E-05
70.93264	6.9474E-06	1.65384E-02	2.31545E-02	1.3240E-02	1.3779E-03	2.1957E-04	7.9471E-05	4.2763E-05
74.23224	5.5925E-06	1.41621E-02	2.07461E-02	9.41600E-03	5.9693E-04	1.5503E-04	5.0478E-05	3.4199E-05
77.53584	4.5985E-06	1.21419E-02	1.79596E-02	6.59792E-03	5.9465E-04	1.1155E-04	4.6689E-05	2.7661E-05
80.93344	3.7497E-06	1.02827E-02	1.51218E-02	4.59279E-03	4.0164E-04	8.1667E-05	3.6513E-05	2.2614E-05
84.34304	3.12169E-06	9.6281E-03	1.24593E-02	3.19504E-03	2.7629E-04	6.0751E-05	2.8910E-05	1.8661E-05
87.69364	2.61785E-06	7.19157E-03	1.00957E-02	2.23079E-03	1.9343E-04	4.5862E-05	2.3147E-05	1.5532E-05
91.05024	2.1287E-06	5.96704E-03	8.08324E-03	1.56783E-03	1.3772E-04	3.5101E-05	1.8724E-05	1.3048E-05
94.40234	1.83429E-06	4.93722E-03	6.41843E-03	1.1113E-03	9.9634E-05	2.7204E-05	1.5299E-05	1.1030E-05
97.75744	1.61539E-06	4.07960E-03	5.06993E-03	7.95490E-04	7.3163E-05	2.1390E-05	1.2597E-05	9.3934E-06
101.11104	1.39354E-06	3.3702E-03	3.99383E-03	5.75391E-04	5.4825E-05	1.6902E-05	1.0461E-05	8.0503E-06
104.46434	1.20915E-06	2.75631E-03	3.14372E-03	4.2069E-04	4.1112E-05	1.3533E-05	8.7547E-06	6.9484E-06
107.81624	1.0461E-06	2.30690E-03	2.47653E-03	3.10947E-04	3.1404E-05	1.0938E-05	7.3771E-06	5.0161E-06
111.17134	9.2437E-07	1.9138E-03	1.95497E-03	2.3201E-04	2.4266E-05	8.9155E-06	6.2570E-06	5.2433E-06
114.52544	3.1481E-07	1.5917E-03	1.54777E-03	1.7537E-04	1.8953E-05	7.3267E-06	5.3394E-06	4.5926E-06
117.87904	7.2080E-07	1.32754E-03	1.22986E-03	1.3744E-04	1.4953E-05	6.0658E-06	4.5831E-06	4.0420E-06
121.23264	6.4937E-07	1.11060E-03	9.8121E-04	1.0299E-04	1.1908E-05	5.0571E-06	3.9547E-06	3.5638E-06
124.58624	5.71129E-07	9.32126E-04	7.85531E-04	5.00637E-05	9.56817E-06	4.24520E-06	3.4246E-06	3.1664E-06
CUR. CN RANGE	9.94746E-01	9.99858E-01	9.99966E-01	9.99997E-01	9.99999E-01	9.99999E-01	9.99931E-01	9.98375E-01
MEAN OF R	9.31689E+00	6.52012E+01	7.02532E+01	5.74464E+01	4.22618E+01	2.95067E+01	2.00244E+01	1.33766E+01
VARIANCE OF R	2.00377E+01	5.41776E+02	3.67443E+02	1.65749E+02	9.84833E+01	7.64556E+01	6.25363E+01	4.94035E+01
STD. DEV OF R	4.47635E+00	2.32761E+01	1.91689E+01	1.29904E+01	9.92390E+00	8.74339E+00	7.90799E+00	7.02912E+00
DO AGAIN? :	1							
ENTER NUMBER OF SAMPLES :	28							
ENTER SAMPLE PAIRS: FIRST P, THEN R.								
:	110.120	116.401						
:	109.933	62.509						
:	111.339	26.574						
:	124.250	64.420						
:	143.463	51.311						

TABLE 4.5.2. Continued



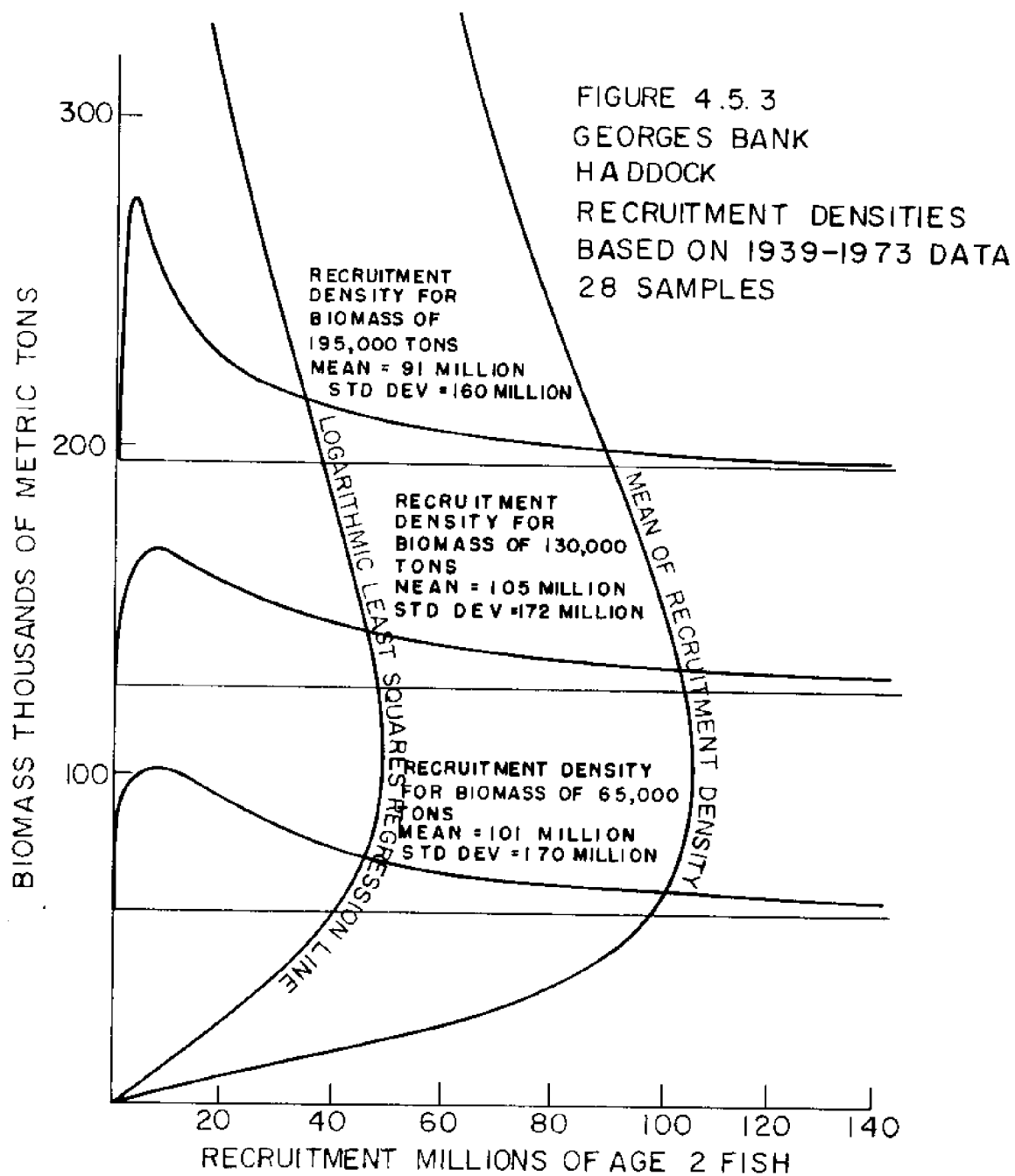
(called R) and the value of the density at its peak. Finally, the program actually computes the posterior density on recruitment for eight different adult stock levels and outputs the mean and variance of these eight densities.

Graphically, these results for yellowtail are illustrated in Figure 4.5.2 , which shows three of these densities, together with their means as a function of adult biomass. We have also redrawn the transformed least-square regression line on this figure. This line is simply Figure 4.5.1 with the axes reversed. First, the difference between the mean of the recruitment density conditional on stock level and the regression line points out that $\hat{\alpha} = \exp(\log \hat{\alpha})$ and $\hat{\beta}$ are not unbiased estimators of α and β . This is a product of the fact that the least-squares procedures has been applied to the log of the sample data and not the data itself. To put it another way, all the log-student densities are skewed--possibly highly so. The mode of these densities is always less than the mean. In all our results so far, the mode is also less than the transformed least-square estimator.* Hence, the least-square estimator appears to compromise between the mode and the mean. Secondly and much more importantly, note the considerable spread-outness of these densities. The ratio of the standard densities to the mean runs from .5 (at the very low and very high levels of stock) to .95 at intermediate levels. This implies that we can reasonably expect to observe recruitments which are a factor of two or more away from our "best guess," whether

*This can probably be proved, but the algebra's pretty forbidding.

that best guess be in terms of transformed least squares, the mean, or the mode. In short, these densities faithfully reflect our uncertainty about future recruitment given the assumptions underlying the analysis--principally the Ricker form postulate--and the fluctuations in recruitment observed in the data.

Actually, the yellowtail recruitment data is reasonably well-behaved. We have applied the same analysis to thirty years of haddock data taken from Clark [1977a]. Clark's data covers the period 1939 to 1973. The results are shown in Figure 4.5.3 and they can reasonably be regarded as a mess. The least-squares regression line has a mode at a stock level of about 100,000 tons, at which point the estimate of recruitment is about 50 million age 2 fish. However, the mean of the recruitment density is just about twice these least-square levels. The reason for this gross difference between the mean and the maximum likelihood estimates becomes clear when one combines these curves with a few of the recruitment densities, as has been done in Figure 4.5.3. Note the relationship between the mean and the standard deviation. The standard deviation is roughly twice the mean. This in turn is a reflection of the large amount of scatter in the data. Now the only way we can obtain a mean which is small with respect to the standard deviation in a density which is restricted to positive values is with extreme skew. As you will note, these densities have sharp peaks at very low levels of recruitment--



5-10 million fish--but they also have very long tails. The mean of the density is typically ten times the mode. With densities of such high skew we can reasonably expect order-of-magnitude fluctuations in recruitment for a given level of adult stock. In short, the analysis is telling us that our uncertainty as to future haddock recruitment is very high indeed and that "best guesses" at future recruitment, whether they be based on least squares, the mean, or the mode, will almost certainly be quite far from actual recruitment.*

Our uncertainty as to future recruitment is a fact of life. It is not an excuse for not managing the fishery. Rather, it implies the need for a model which incorporates this uncertainty into its computations. This is the purpose of Mode C of the RECRUIT subroutine. As mentioned earlier, the statistics required to compute the recruitment density are transferred from the RICKER results to the Species file and from this file are available to FISHDYN1.** In Mode C, RECRUIT uses this information to reconstruct the family of recruitment densities. Then each time RECRUIT is called, it produces a sample of the log-student recruitment density corresponding to the current adult stock level. This sample is produced in such a way that the probability of each such

*Part of the haddock problem may well be the overly restrictive Ricker form. The authors will feel much more comfortable with results such as Figure 4.5.4 when they are based on the more general Gamma form.

**The RICKER routine is not part of FISHDYN1 proper. The only time it is run is when one wishes to change or update past stock-recruitment data for a particular species--perhaps once a year. The results are transferred to the appropriate species file manually.

sample's occurring is the same as the probability of that recruitment's occurring under this recruitment density.*

This procedure is called Monte Carloing. Under Monte Carlo sampling, the results of any particular run of FISHDYN1, the recruitment, the resulting stock levels through time, the corresponding catch, and the resulting fisherman's surplus and fish consumer's surplus are all random variables. In order to obtain insight on the distribution of these random variables, it is necessary to repeat such simulations a number of times, holding everything but the recruitment constant. Suppose fifty such simulations are run. The results will include fifty different samples of present-valued fisherman's surplus. One can then examine the histogram of these fifty samples, and compute their average and their variance to obtain an idea not only as to the likely values of fisherman's surplus under the given level of effort, but also the possible fluctuations in fisherman's income due to the possible fluctuations in recruitment.

Table 4.5.3 shows the results of a typical run of FISHDYN1 using the Monte Carlo recruitment mode. The input portion is the same as in the earlier recruitment modes with the exception that FISHDYN1 must be told the number of Monte Carlo simulations desired. In this case, the user requested twenty such runs, requesting non-specific output for only two of these twenty.

*The rejection method based on a pair of properly transformed uniformly distributed pseudo-random numbers is used. See Devanney [1972] for a description of this method.

M.I.T. SINGLE SPECIES, FISHERY SIMULATOR INVOKED.
PLEASE ENTER REPORT TITLE: YELLOWTAIL PRODUCTION RUN. ROUGHLY 4200 DAYS EFFORT.

PLEASE ENTER SPECIES NAME: YEL

PLEASE ENTER RECRUITMENT OPTION: 5

MONTE CAPLO SIMULATION REQUESTED. ENTER NO. OF RUNS: 20

ENTER NUMBER OF RUNS FOR WHICH RUN-SPECIFIC OUTPUT DESIRED: 2

DO YOU WANT TERSE(T), SHOPT(S), LONG(L) OR VEPBOSE(V) OUTPUT?: T

ENTER ANY CHANGES TO SPECIES DATA: SPECIES.TAUMAX=2000;

PLEASE ENTER VESSEL EFFORT OPTION: 1

ENTER NUMBER OF ACTIVE VESSELS IN EACH SIZE CATEGORY IN ORDER

: 28 0 0 0

PLEASE ENTER CATCH OPTION: 1

PLEASE ENTER ANY CHANGES TO VESSEL CHARACTERISTICS:;

PLEASE ENTER QUOTA OPTION: 1

ENTER ANNUAL QUOTA IN METRIC TONS: 14000

TABLE 4.5.3

SAMPLE RUN OF FISHDYN1 IN WHICH
USER SPECIFIED MONTE CARLO
RECRUITMENT MODE

YELLOWTAIL PRODUCTION RUN. ROUGHLY 4200 DAYS EFFORT.
SPECIES NAME: YELLOWTAIL FLOUNDER
INITIAL CONDITIONS AS OF JAN 1 INITIAL YEAR AFTER YEAR END AGING. POPULATION IN MILLIONS. BIOMASS IN METRIC TONS.

AGE CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTAL
NAT. MORT. RATE	0.00	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	
WT AT AGE (G/AMS)	0	154	358	521	696	846	965	1061	1131	1172	1213					
NUMBERS	51.1	48.9	29.9	11.6	5.5	2.0	0.8	0.2	0.1	0.0	0.0					99.0
BIOMASS		7531	10704	6044	3828	1700	776	182	86	34	1					30886

PICKER FOM RECRUITMENT ASSUMED. MLE OF ALPHA= 1.31893E+01 MLE OF BETA= 7.03202E-02 SAMPLE SIZE= 11 VARIANCE (LOG)= 3.32924E-02
UNCERTAINTY IN RECRUITMENT SIMULATED BY MONTE CARLO SAMPLING FROM BAYESIAN LOG-STUDENT RECRUITMENT DENSITIES.
INVERSE OF MOMENT MATRIX: NINV(1,1)= 3.27469E+00 NINV(1,2)=NINV(2,1)= -1.11847E-01 NINV(2,2)= 3.92920E-03

MARKET ASSUMPTIONS--MAXIMUM PRICE IS BASELINE FOR CONSUMER SURPLUS CALCULATIONS. PRICES IN \$/METRIC TON ROUND WEIGHT.
UPPER BOUND ON PRICE 1600.00 JANUARY FEBRUARY MARCH APRIL MAY JUNE JULY AUGUST SEPTEMBER OCTOBER NOVEMBER DECEMBER
LOWER BOUND ON PRICE 330 330 330 330 330 330 330 330 330 330 330 330 330 330 330 330
LOWER BOUND ON CATCH 450 450 450 450 450 450 450 450 450 450 450 450 450 450 450 450
UPPER BOUND ON CATCH 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000 2000

FUEL PRICE(\$/MT)=120.00 UNLOADING COST(\$/MT)= 0.00 ICE PRICE(\$/MT)= 20.00 SOCIAL COST OF CAPITAL= 0.05
IND GPT BHP GEAR FISH ICE RUN- FUEL TON- TON. NET MAX CREW INIT ANN. ANN. CREW ANN. MOOP ANN. MOOP VES- REL. AVE. ANN. MAX DIST
-EX HOLD LOAD ING CSMPLNG FUEL AREA CAT. SIZE COST INSP.MANT ANN. OPP. GALL -AGE SEL FISH MAX. DAYS TRIP TO
SIZE SPD TON/ SPD TON/ SQ. TON/ KILO COST COST COST COST COST COST LIFE POW- CATCH AT LNTH FISH
TONS TONS KNTS DAY KNTS DAY MTPS TON \$ S (THOUSAND DOLLARS PER YEAR) ER T/DAY SEA DAYS GPND
1 75 325 0781 30 5 9.0 1.60 0.0 0.00 0 0 5 180 8 18 20 50 13 0 20 0.00 5 200 10 0
1 CATCH VARIATION= 0.50 DAYS FISHED PER DAYS ABSENT= 0.67 MONTHLY FIXED EXPENSES= 8000 MONTHLY VARIABLE EXPENSES= 4448

TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.

CHANGE IN CONSUMER INCOME= 154274 CHANGE IN FISHERMEN INCOME= 53766 CHANGE IN REAL NATIONAL INCOME= 208040 RUN NO. 1

TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	18001	CHANGE IN REAL NATIONAL INCOME=	108631	RUN NO. 13
CHANGE IN CONSUMER INCOME=	90631	CHANGE IN FISHERMEN INCOME=		
TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	46916	CHANGE IN REAL NATIONAL INCOME=	187932	RUN NO. 14
CHANGE IN CONSUMER INCOME=	141016	CHANGE IN FISHERMEN INCOME=		
TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	16065	CHANGE IN REAL NATIONAL INCOME=	108452	RUN NO. 15
CHANGE IN CONSUMER INCOME=	92387	CHANGE IN FISHERMEN INCOME=		
TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	53275	CHANGE IN REAL NATIONAL INCOME=	207613	RUN NO. 16
CHANGE IN CONSUMER INCOME=	154338	CHANGE IN FISHERMEN INCOME=		
TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	53656	CHANGE IN REAL NATIONAL INCOME=	207570	RUN NO. 17
CHANGE IN CONSUMER INCOME=	153914	CHANGE IN FISHERMEN INCOME=		
TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	53405	CHANGE IN REAL NATIONAL INCOME=	207564	RUN NO. 18
CHANGE IN CONSUMER INCOME=	154159	CHANGE IN FISHERMEN INCOME=		
TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	53918	CHANGE IN REAL NATIONAL INCOME=	208943	RUN NO. 19
CHANGE IN CONSUMER INCOME=	155026	CHANGE IN FISHERMEN INCOME=		

YELLOWTAIL FLOUNDER YELLOWTAIL PRODUCTION RUN. ROUGHLY 4200 DAYS EFFORT.

YEAR	INITIAL CATCH	YEAREND RECRUIT	INITIAL CATCH	YEAREND ACTIVE	ANNUAL CONSUMER	FISHERMEN	OPERATING	NEW	770824					
	BIOMASS	WEIGHT	BIOMASS	POP.	FLRET QUOTA	REVENUE	OUTLAYS	INVESTMENT	AVERAGE					
	-----METRIC TONS-----	-----MILLIONS OF FISH-----	POP.	POP.	POP.	THOUSANDS OF DOLLARS	THOUSANDS OF DOLLARS	THOUSANDS OF DOLLARS	PRICE					
1976	30886	9197	12752	0	99	29	41	28	14000	10469	8165	4182	5040	887.79
1977	28077	9174	10484	51	92	30	34	28	14000	10444	8160	4182	0	889.48
1978	30556	9190	12491	89	124	37	51	28	14000	10461	8163	4182	0	888.34
1979	35698	9224	16653	87	138	36	64	28	14000	10498	8171	4182	0	885.84
1980	42194	9254	21931	87	152	33	79	28	14000	10530	8178	4182	0	883.65
1981	46817	9271	25694	66	145	29	79	28	14000	10548	8181	4182	0	882.46
1982	47580	9275	26314	49	128	25	71	28	14000	10552	8182	4182	0	882.19
1983	45165	9269	24344	42	112	23	60	28	14000	10546	8181	4182	0	882.60
1984	39747	9252	19932	32	93	22	46	28	14000	10528	8177	4182	0	883.84
1985	35100	9230	16158	48	94	25	44	28	14000	10504	8172	4182	0	885.44
1986	28697	9184	10978	32	75	24	29	28	14000	10455	8162	4182	0	888.73
1987	26348	9153	9098	68	97	33	34	28	14000	10421	8155	4182	0	891.03
1988	24500	9126	7704	60	93	35	29	28	14000	10392	8149	4182	0	893.04
1989	19316	9020	3936	43	73	33	14	28	14000	10274	8126	4182	0	900.90
1990	19591	8981	3800	84	99	45	19	28	14000	10228	8118	4182	0	903.86
1991	15139	8521	826	49	68	38	4	28	14000	9487	8017	4182	0	940.87
1992	10133	6114	116	56	60	36	1	28	14000	5761	6374	4182	0	1042.44
1993	9429	5695	96	60	60	36	1	28	14000	5659	5802	4182	0	1018.75
1994	5508	3434	14	34	35	22	0	28	14000	3051	3783	4182	0	1101.72
1995	4948	3094	11	32	32	20	0	28	14000	2703	3463	4182	0	1119.01
1996	4723	2959	10	31	31	19	0	28	14000	2373	3381	4182	0	1142.78
1997	4947	3094	11	32	32	20	0	28	14000	2704	3461	4182	0	1118.74
1998	4398	2761	8	28	28	18	0	28	14000	2284	3148	4182	0	1140.20
1999	2817	1783	4	18	18	12	0	28	14000	1222	2237	4182	0	1254.30
2000	8410	5124	61	55	55	33	0	28	14000	4899	5321	4182	0	1038.35

TOTAL PRESENT VALUED CHANGES IN REAL INCOME RELATIVE TO NO EXPLOITATION OF THE STOCK.	40272	CHANGE IN REAL NATIONAL INCOME=	170922	RUN NO. 20
CHANGE IN CONSUMER INCOME=	130650	CHANGE IN FISHERMEN INCOME=		

STATISTICS ON CHANGES IN PRESENT VALUED INCOME FOR 20 MONTE CARLO SIMULATIONS

THESE RUNS BASED ON PICKER STOCK-RECRUITMENT HYPOTHESIS. SAMPLES DRAWN FROM RESULTING SET OF LOG-STUDENT RECRUITMENT DENSITIES

	SAMPLE MEAN	SAMPLE VARIANCE	SAMPLE S.D.
P.V. FISH CONSUMER INCOME	135853	6.032957E+08	24562
P.V. FISHERMEN INCOME	43368	1.934950E+08	13910
P.V. NATIONAL INCOME	179221	1.479015E+09	38458

READY

The output is arranged as before, except that for all but the tenth and twentieth runs only the present-value totals are printed. The results for the tenth and for the twentieth runs are interesting. The level of effort specified in these runs is a little too high. It can push the fishery into the unstable portion of the recruitment curve, if recruitment is a little lower than expected. But in the twentieth run, the fishery was quite fortunate in receiving unusually high recruitment in the third through fifth years. As a result, the fishery didn't get into real trouble until the late 1980s. In the tenth run, however, the fishery was cursed with slightly lower than expected recruitment in the early years. As a result, the fishery was already in very bad shape in the very early 1980s. In terms of present-valued national income, the resulting difference is almost sixty million dollars.

Examining the other eighteen runs, we see that the present-valued national surplus ranges from a high of \$208 million to a low of \$108 million. A histogram of these results is shown in Figure 4.5.4. The average of the national surplus is about \$179 million and the sample standard deviation is about \$38 million. These statistics are printed at the end of the output. One is cautioned against using these statistics as if the national surplus were distributed Normally. As Figure 4.5.4 shows, the distribution is clearly non-Normal. Either recruitment is sufficiently high that the stock stays on the stable

FIGURE 4.5.4. HISTOGRAM OF SOCIAL SURPLUS
FOR THE 20 RUNS OF TABLE 4.5.3



portion of the recruitment curve throughout the simulation, in which case the national surplus is between \$200 million and \$210 million, or recruitment falls off sufficiently to pull the stock on the wrong side of the peak, in which case it is a great deal less. Such a process is asymmetric in the extreme. Nonetheless, the sample standard deviation can be used as a very rough measure of the sort of variability induced in the overall economic measures by out uncertainties as to future recruitment.

CHAPTER 5

RESULTS OF CONSTANT EFFORT GEORGES BANK
YELLOWTAIL FLOUNDER RUNS5.1 Introduction

FISHDYN1 has been applied to the present situation facing the Georges Bank yellowtail fishery. As indicated in Table 5.1.1, we have made some sixty production runs using all three recruitment modes. All these runs were for the period 1976 to 2000. In these runs, we varied the level of effort directed at the stock from ten vessels fishing the stock full-time (about 225 days absent per year per vessel, or 150 days fished per year) to fifty.* In these sample runs, only one vessel category was employed--a sixty-five foot, seventy-five ton sidetrawler typical of the mainstay of the New England yellowtail fleet--and the annual level of effort was maintained constant throughout the 1976 to 2000 period. The characteristics assumed for this "standard vessel" are shown in Table 4.4.1. The cost figures are based on a variety of sources and in total are believed to be generous. Note that the entire analysis is in real (1976 dollars) terms. Thus, the 5% real cost of capital translates to a market interest rate of 10%-12% given current inflation rates. Most of the cases shown in Table 5.1.1 were run twice, once with an unlimited quota, and then repeated with a constant annual quota of 10,000 tons--the current Regional Council-mandated level.

*We also modelled, for comparison, a few zero-effort runs. A blank in Table 5.1.1 indicates that the corresponding runs were not made.

TABLE 5.1.1.1

SUMMARY OF CONSTANT-EFFORT YELLOWTAIL PRODUCTION RUNS (PRESENT-VALUED SOCIAL SURPLUS IN MILLIONS OF 1976 DOLLARS)

Level of Effort (Number of 75-Ton Trawlers)	Constant Recruitment			Deterministic Ricker-Form			Stochastic Simulation of Ricker-Form Recruitment Based on Bayesian Regression of 1963-1975 Data (20 Samples)					
	At Average of 1963-1975 Data (51 Million Age 2 Fish)			Recruitment Based on Least-Squares Regression of 1963-1975 Data			No Quota		10,000 Ton Quota		Sample Mean	Sample Std Dev
	No Quota	10,000 Ton Quota		No Quota	10,000 Ton Quota		Sample Mean	Sample Std Dev	Sample Mean	Sample Std Dev		
0	0.0	0.0		0.0	0.0							
10	55.2	55.2		55.1	55.1		55.1	Nil	55.1	Nil		
15					82.4							
20	164.1	164.1		163.6	163.6		163.3	Nil	163.6	Nil		
23		185.4										
24		190.0										
25	186.7	186.7		196.4	196.4		196.3	.4	196.4	.4		
26					200.9				199.2	6.7		
27					204.9				186.0	31.8		
28					164.8				179.2	38.5		
30	107.3	107.3		89.5	89.5		134.2	44.5	134.2	44.5		
35				46.8	56.8		60.6	16.9	64.2	14.3		
40	62.3	66.5		21.8	36.0		34.7	17.3	47.2	19.7		
50				-12.4	5.5		-7.7	13.0	20.1	20.0		

The initial (January 1, 1976) population growth curve and natural mortality assumptions used in these runs are given in Table 5.1.2. The initial population distribution is based on 1975 ICNAF stock assessments [ICNAF, 1976]. The growth curve is taken from ICNAF Secretariat [1976], and the natural mortality rate, 0.2 for all age groups, is that assumed in most ICNAF yellowtail population analyses. The demand curve used is the dotted line in Figure 4.4.1, and represents the best of the fits in terms of standard error of the functional forms we studied. The stock-recruitment time series upon which these runs were based is displayed in Table 4.5.1. The basic source here is Parrack [1976], but the Parrack figures for each year are in millions of fish in each age class. We converted these numbers to adult biomass using the growth curve of Table 5.1.2. In this conversion, we assumed knife-edge recruitment at the beginning of age 2 and we further assumed that all age 2 fish immediately entered the spawning stock.* The initial adult biomass under these assumptions is 30,886 tons.

All these assumptions, particularly the last, are arguable but before we become embroiled in arguments over assumptions, let us examine some of the results. At this point, anyway, the qualitative response of the model to

*In reality, the Georges Bank yellowtail spawns in spring, March through June. However, the age 2 year class are not fully recruited to the exploited stock until the fall of their third year of life. Thus, the errors with respect to both initial spawning and initial recruitment are in a sense offsetting. This is no excuse for not doing a better job on seasonal spawning and growth.

TABLE 5.1.2
BIOLOGICAL ASSUMPTIONS USED IN YELLOWTAIL PRODUCTION RUNS

Age Class	Weight at Age (Grams)	Natural Mortality Rate (%/%)	Initial (1/1/76) Population (Millions)
1			51.1 ^a
2	154	.2	48.9
3	358	.2	29.9
4	521	.2	11.6
5	696	.2	5.5
6	846	.2	2.0
7	965	.2	0.8
8	1,061	.2	0.2
9	1,131	.2	0.1
10	1,172	.2	0.0
11 ^b	1,213	.2	0.0

^aThis is January 1, 1977 recruitment in all runs.

^bAssumed to be maximum possible age in fishery.

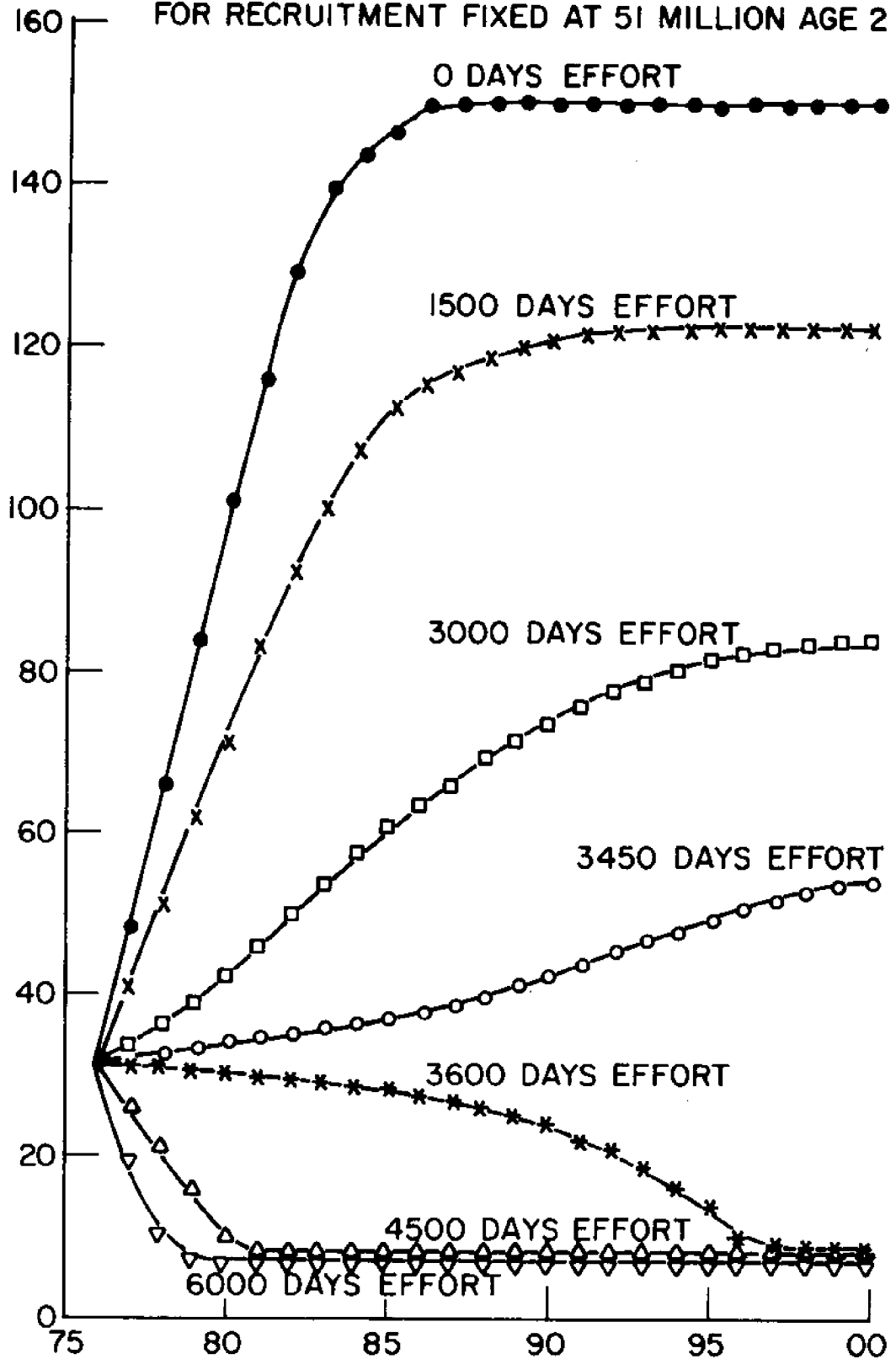
variation in effort and recruitment mode are at least as interesting as the quantitative details of the output. Other assumptions with respect to the above variables can, of course, be run at will.

5.2 Results for exogenously fixed recruitment runs

Average yellowtail recruitment at age 2 over the period 1963-1975, according to PARRACK, Table 4.5.1, is 51.1 million fish. In our first set of production runs, recruitment was fixed at this level, regardless of the size of the stock. The resulting biomass through time is shown in Figure 5.2.1 for a range of levels of effort. The combination of fixed recruitment and constant level of effort in FISHDYN1 guarantees that the model will approach steady state in a completely damped fashion, that is, without any overshoot. However, in some cases, it can take a good deal of time before steady state is attained--as long as twenty years.

It is clear that the present (1976) stock level is in equilibrium only for about 3,500 days effort under this set of assumptions. For levels of effort below this, the stock grows. For levels of effort above this, the stock decreases. The rather curious phenomenon at the bottom of the figure where a large range of levels of effort leads to the same equilibrium stock levels results from the fact that all these effort levels are high enough to eventually push the fishery to the point where it consists only of newly recruited two-year-olds. Since the level of two-year-old recruitment is assumed to be independent of stock size in these runs, the same number of fish are entering the fishery, whereupon they are immediately caught. If we

FIGURE 5.2.1 ADULT BIOMASS THRU TIME
(IMMEDIATELY AFTER ANNUAL AGING AND GROWTH)
FOR RECRUITMENT FIXED AT 51 MILLION AGE 2 FISH



had assumed that two-year-olds did not contribute to the spawning stock, this point would represent virtual extinction. At these higher levels of effort, the only difference is how soon the fishery reaches this state.

While fixed recruitment and constant level of effort will lead to steady state without fluctuation in the FISHDYN1 model, it is a very narrowly stable, steady state in the sense that small changes in level of effort can lead to greatly different steady-state stocks. For no fishing, the steady-state stock level is about 150,000 metric tons. Adding just ten vessels full-time to the fishery decreases this steady-state level some 30,000 tons. Another ten vessels drop it another 40,000 tons. At about 3,500 days effort, a difference of one vessel full-time (150 days fished) is sufficient to make the difference between moderate growth and virtual extinction. According to this model, the difference between underfishing and overfishing is quite fine indeed. We will have cause to refer back to this behavior when we study the more sophisticated recruitment models below.

The overall economic results for the fixed recruitment runs are summarized in Table 5.2.1 and displayed in Figure 5.2.2. Since many people are uncomfortable in thinking about present values, the various surpluses have been converted to equivalent amount of real (1976) income received annually for the twenty-five-year period 1976-2000 on the right-hand scale in Figure 5.2.2. However, in using the right-hand scale, remember that the actual income flows will in general

TABLE 5.2.1
 SOCIAL SURPLUS, FISHERMAN SURPLUS, AND CONSUMER SURPLUS
 VERSUS FISHING EFFORT FOR FIXED RECRUITMENT YELLOWTAIL
 SIMULATIONS (ALL FIGURES ARE PRESENT VALUES IN MILLIONS
 OF 1976 DOLLARS), 10,000 TON ANNUAL QUOTA

Fishing Effort (Days Fished) Annually	Fisherman Surplus	Consumer Surplus	Social Surplus
0	0.0	0.0	0.0
1500	55.2	0.0	55.2
3000	64.8	99.3	164.0
3450	60.7	124.6	185.3
3600	59.2	130.8	190.0
3750	42.4	104.9	147.3
4500	13.5	93.7	107.2
6000 ^a	-22.9	89.4	66.5

^aFor this level of effort and only for this level of effort, the 10,000 ton quota limited the catch, and then only in 1976, 1977, and 1978. For these three years, the actual effort employed under the quota was 5,200 days, 5,700 days, and 5,900 days. After 1978, the stock was in such bad shape that the quota was no longer limiting.

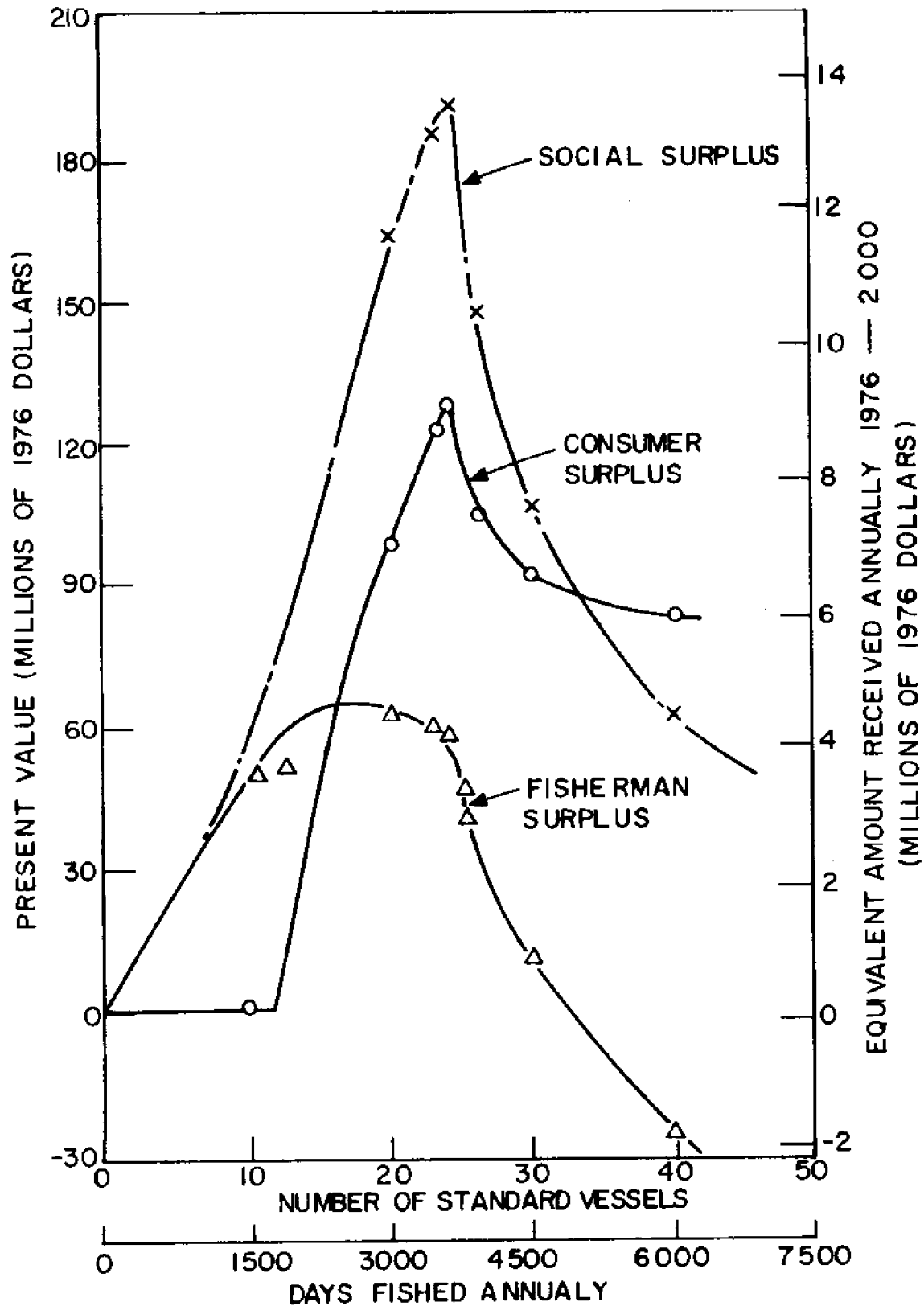


FIGURE 5.2.2. PRESENT VALUED SURPLUSES FOR
FIXED RECRUITMENT, 1976-2000
YELLOWTAIL RUNS REAL COST OF
CAPITAL = 5 %

be distributed in a very non-uniform manner throughout the period due to variations in landings, variations in price, and periodic capital investment. For example, Figure 5.2.3 shows the actual income flows for fishermen and consumers through time for the twenty-five-vessel, 3,750-day effort run. The actual annual consumer's surplus drops from \$9.3 million to \$4.3 million during the period. The equivalent constant amount is about \$7 million, as can be seen from Figure 5.2.2. Only in steady state will the annual income flows be constant.

Examining Figure 5.2.2, we note that under this set of assumptions, fisherman's surplus will be maximized at about 2,000 days of effort per year. In the terminology of Chapter 2, this is the Maximum Monopoly Profit (MMP) point. Fisherman's surplus drops to zero at about 5,000 days of effort. This is the long-run Free Entry level of effort for this set of runs. The fisherman's surplus curve is not quite double-humped because our demand curve is not quite inelastic. Consumer's surplus is maximized at about 3,600 days of effort and the Maximum Social Surplus level of effort--the Maximum National Income (MNI) point--is just to the left of this. However, any point between 3,000 and 3,600 days of effort combines near-maximal fisherman's surplus with near-maximal consumer's surplus. Thus, in this case there is considerable room for agreement between fish producers and fish buyers.

The consumer's surplus is zero for levels of effort less than 1,500 days per year, for the resulting landings are so low that we are on the leftmost flat portion of the demand curve in Figure 4.4.1. That is, at these low levels

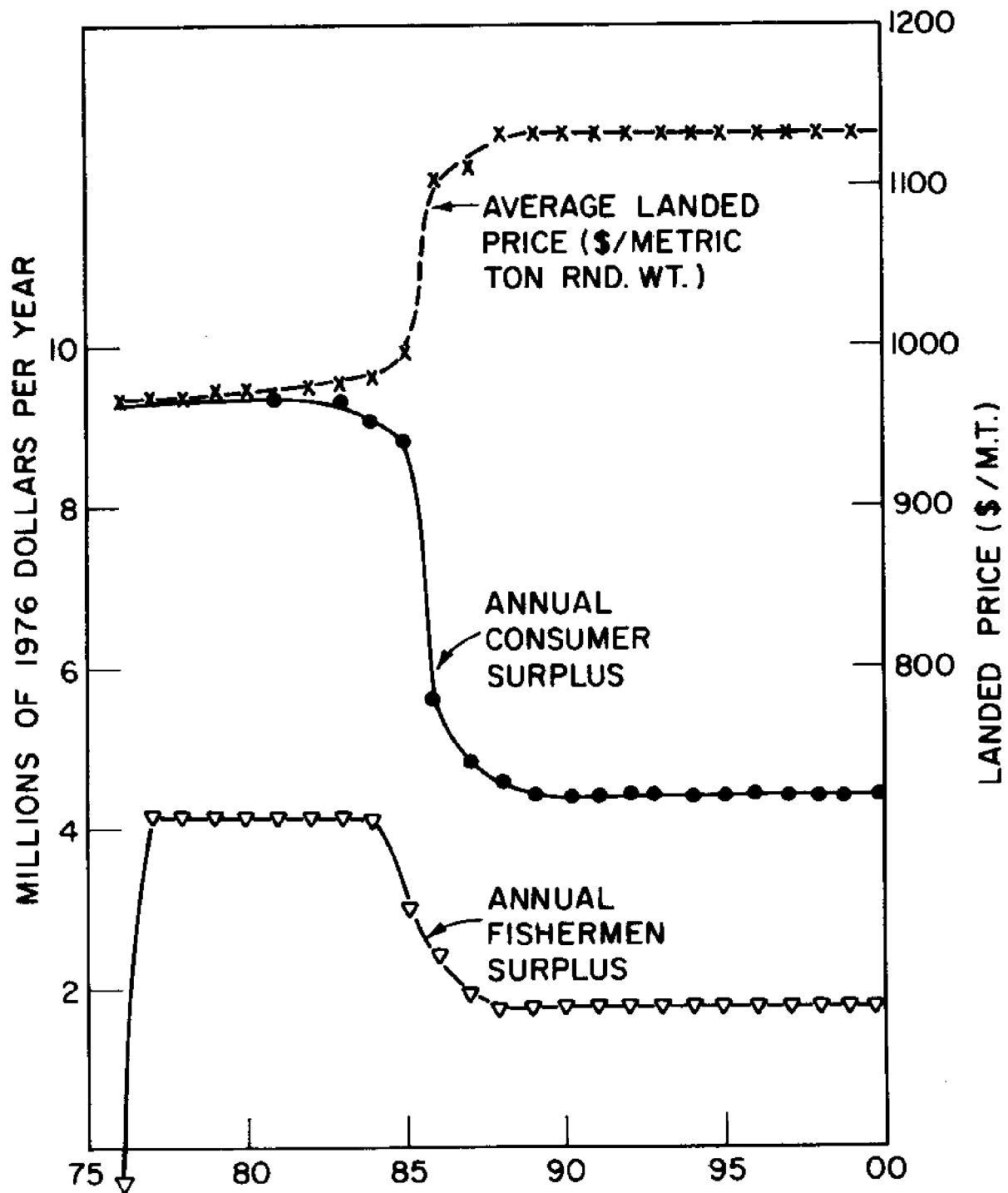


FIGURE 5.2.3. TIME SERIES OF INCOME FLOWS AND LANDED PRICE FOR FIXED RECRUITMENT YELLOWTAIL RUN. 3750 DAYS FISHED PER YEAR LEVEL OF EFFORT, 25 'STANDARD' VESSELS

of landings price is so high that all fish purchasers are indifferent between buying the fish and not buying them. The reason why the consumer surplus does not go to zero at very high levels of effort is the present value associated with the high catches in the period 1976 to 1980 during which time the current stock is being virtually wiped out. During this period, the consumer is getting the advantage of rather high landings at low prices. Even though the catch quickly drops to very low levels thereafter, this overexploitation is economically preferable to no exploitation, no catch at all at any time, which is the baseline--the zero point--for our consumer surplus calculations. In this case at least, other less drastic management strategies are much better from both the consumer's and fisherman's points of view.

In interpreting Figure 5.2.2, it is important to remember, among other things, that we are comparing only an extremely small subset of all possible management strategies--those with constant levels of effort. Strategies in which the effort is properly varied through time will in general be able to do better than the best of the constant-effort strategies. However, the proper way of determining such strategies is dynamic programming, which has not been implemented in the current version of FISHDYN1.* Hence, throughout this

*FISHDYN1 does have the capability of running a given variable-effort strategy. However, determining the best of all variable-effort strategies by trial and error using FISHDYN1 would result in astronomical computer bills.

report, we will be dealing exclusively with constant-effort strategies.

5.3 Results from the deterministic Ricker-form recruitment runs

When we move to Recruitment Mode B and allow recruitment to depend on adult biomass according to the Ricker formulation fitted to the available yellowtail data, keeping all other assumptions the same, we observe a number of new and extremely interesting phenomena. Consider Figure 5.3.1, which displays adult biomass through time assuming no fishing. Clearly we now have a strongly cyclic behavior. Under this set of assumptions, the equilibrium fallow stock is about 60,000 tons, well above the 1976 level of 31,000 tons. But at the same time, it is almost meaningless to talk about an equilibrium level, for in moving to that equilibrium level, the stock overshoots its target by about as much as the original difference between present stock and the eventual target level. Upon overshooting, it eventually turns around and does the same thing in the opposite direction. The stock behaves like a pendulum. The problem is that the correcting force--the decrease in recruitment as stock sizes grow and increase in recruitment as stock level drops--is so weak and so slow in its influence that by the time it really starts having effect, the stock has passed through the target level and the opposite effect is required. The recruitment through time has also been

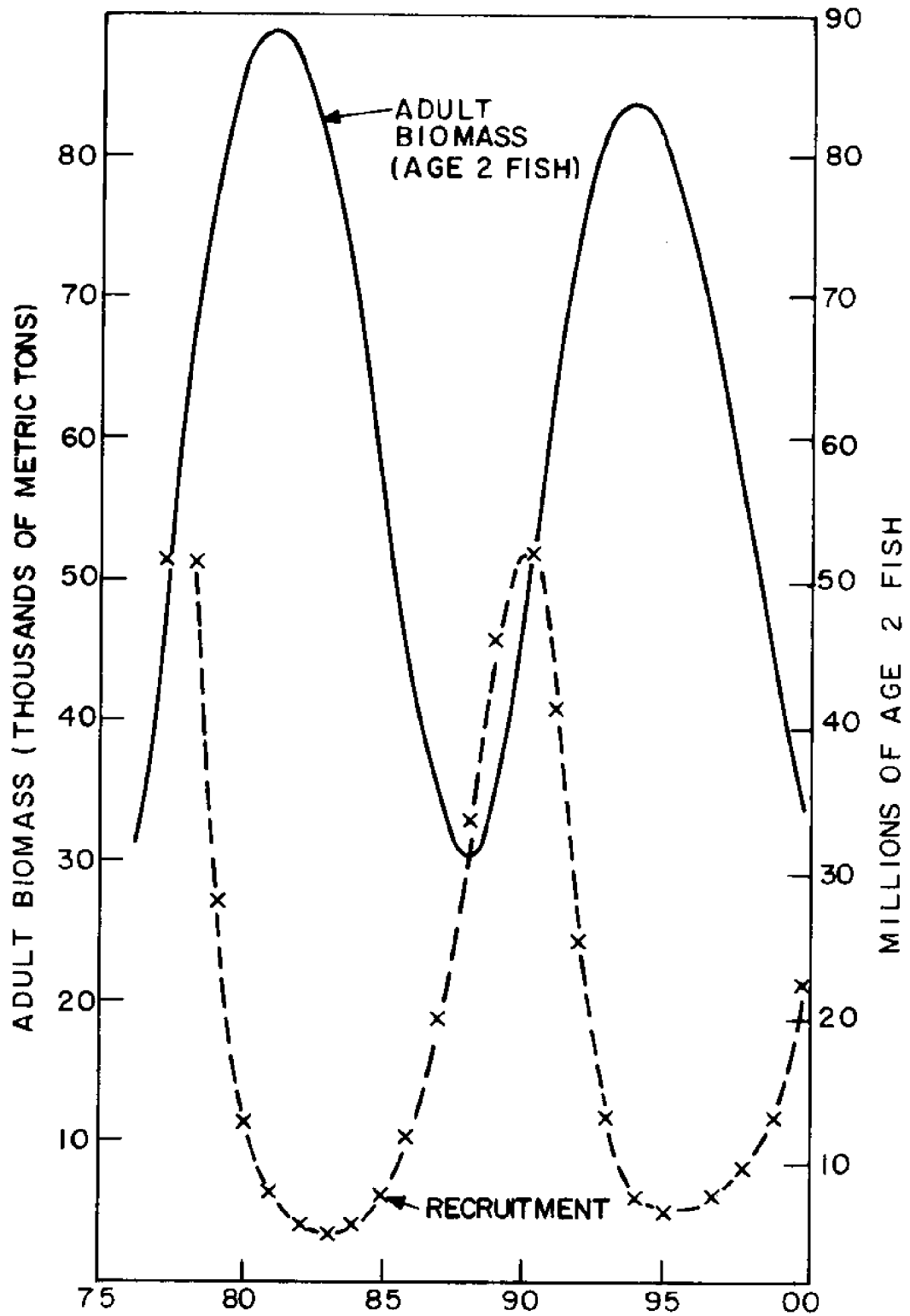


FIGURE 5.3.1 YELLOWTAIL FLOUNDER 1976-2000
SIMULATION, DETERMINISTIC RICKER
RECRUITMENT, NO FISHING EFFORT

plotted on this figure. Note that the recruitment is out of phase with stock size--the higher the stock size, the lower the recruitment, for in this figure the stock always remains on the "stable" portion of the recruitment curve. But the peak in recruitment lags two years behind the trough in adult stock, representing the larval and juvenile growth period. Further, the effect of the newly recruited year class on adult biomass is felt only gradually, as this class grows to full maturity. Hence, there is roughly speaking about a four- or five-year lag between cause and effect. By the time a particular year class reaches maturity, the new stock level will in general be quite different from that which generated this year class.

The system will eventually reach steady state. Each fluctuation is smaller than the last. But the process will be extremely slow. In engineering jargon, we have a very lightly damped, cyclic system with a period (time interval between peaks) of about thirteen years. The damping (the ratio of the magnitude between succeeding peaks) is about 10%. Hence, very roughly speaking, it will take something like 130 years for this system to settle into steady state. Long before that happens, of course, something else would have changed and set up a whole new chain of fluctuations. Such cyclic behavior is the norm rather than the exception in the affairs of both people and nature. As mentioned earlier, fluctuations such as those in Figure 5.3.1 have been observed in a number of essentially fallow fish stocks. To ignore such dynamic

behavior in fisheries management is the height of folly. In any event, as Figure 5.3.1 makes clear, in order to obtain such behavior, it is only necessary to model the lag in the feedback between stock and recruitment.

Figure 5.3.2 shows the fluctuation in adult biomass under the assumption of rather low level of fishing effort. A comparison of Figures 5.3.2 and 5.3.1 makes the point that a constant level of fishing effort can be stabilizing. The period of the fluctuation remains about thirteen years but the damping is over 50% per cycle. Hence, in three or four cycles, the stock will be at its steady state at an equilibrium level of about 50,000 metric tons. We have also shown the total catch through time on Figure 5.3.2. Notice that the catch fluctuates much less violently than the stock. However, the age distribution of the catch changes very significantly in different parts of the cycle.

Table 5.3.1 displays the age distribution of the annual catch throughout the twenty-five year period. Under our simple catch assumptions, the age distribution of the catch and the (mass) distribution of the adult population are identical. The initial population distribution is extremely young, representing the current unhealthy and overexploited state of the Georges Bank yellowtail stock. The first three or four years are characterized by very high recruitment associated with the low initial level of the stock.* However, under the drastically reduced effort level

*As of 1976 at least we were still on the stable portion of the Ricker curve according to our estimates.

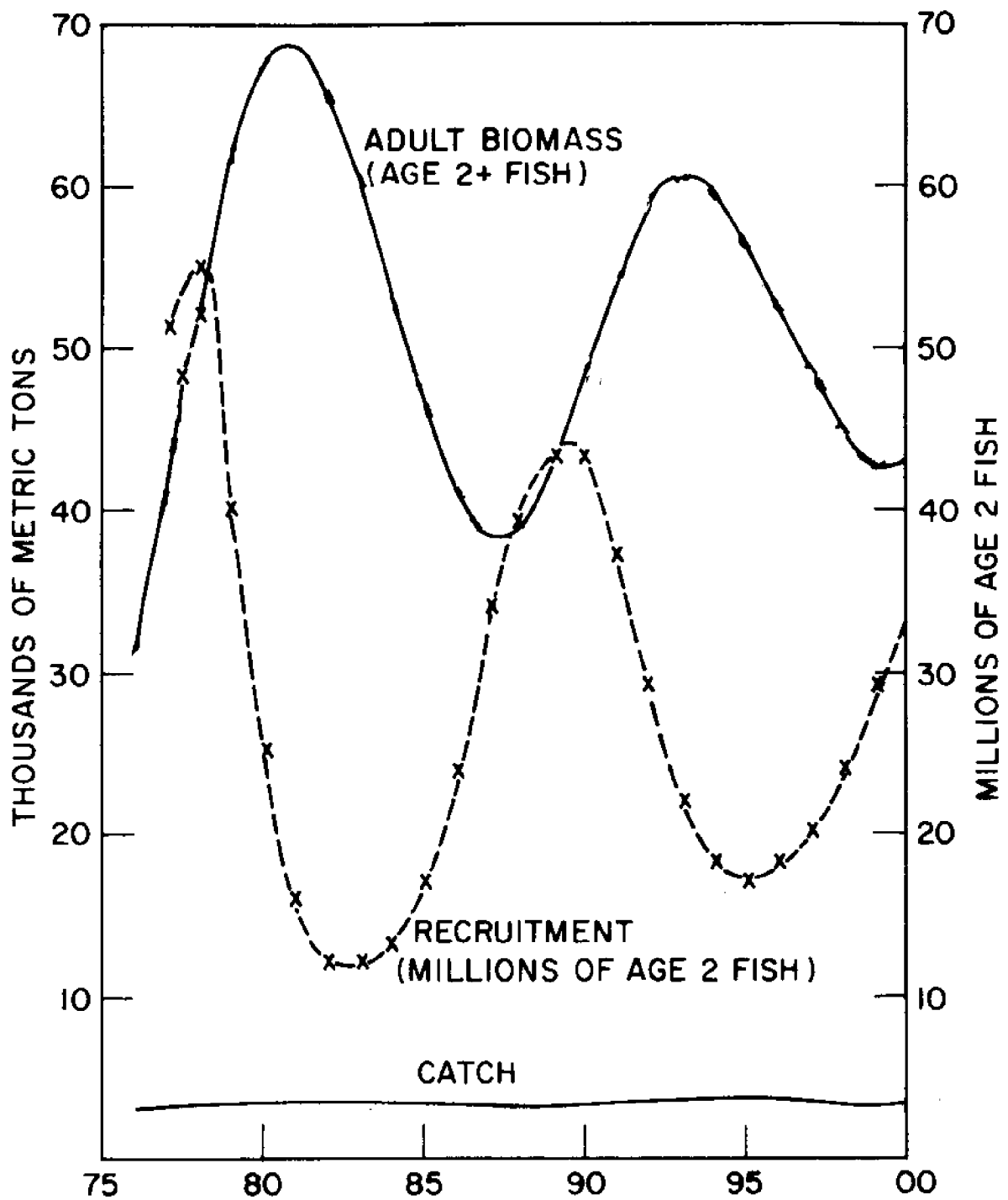


FIGURE 5.3.2 YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 1500 DAYS EFFORT

TABLE 5.3.1

CATCH DISTRIBUTION THROUGH TIME IN TONS FOR YELLOWTAIL.

1500 DAYS PER YEAR RUN, DETERMINISTIC RICKER RECRUITMENT.

UNDER ASSUMPTIONS GOVERNING THESE RUNS, AGE DISTRIBUTION OF CATCH AND AGE DISTRIBUTION OF ADULT POPULATION BY WEIGHT ARE THE SAME

Year	Age										Total
	2	3	4	5	6	7	8	9	10	11	
76	812	1155	652	413	183	84	20	9	4	0	3332
77	657	977	842	442	251	105	45	11	5	2	3336
78	<u>553</u>	835	779	619	295	158	64	26	6	3	3339
79	346	<u>783</u>	741	634	462	206	106	42	17	4	3341
80	200	542	<u>773</u>	671	524	359	154	77	29	12	3341
81	124	339	578	<u>762</u>	602	441	293	122	54	23	3342
82	97	224	384	602	<u>725</u>	538	380	245	99	48	3341
83	99	183	265	416	595	<u>676</u>	483	331	208	84	3340
84	126	192	222	294	421	565	<u>621</u>	431	287	181	3339
85	188	248	236	250	301	403	524	<u>561</u>	378	251	3338
86	287	357	295	257	248	279	361	456	<u>475</u>	320	3336
87	417	509	396	301	238	215	233	292	359	375	3335
88	516	678	518	370	255	190	165	173	211	259	3335
89	523	767	631	443	288	186	133	112	114	139	3337
90	<u>456</u>	758	697	526	336	205	128	88	72	73	3338
91	352	<u>681</u>	709	599	412	247	145	87	59	48	3340
92	255	555	<u>674</u>	645	497	321	185	105	62	41	3340
93	190	425	580	<u>644</u>	565	409	255	143	74	46	3341
94	157	331	446	584	<u>595</u>	487	340	206	112	62	3340
95	152	285	375	485	554	<u>530</u>	419	284	167	91	3340
96	171	281	329	398	467	502	<u>464</u>	356	234	138	3339
97	213	317	327	350	385	424	440	<u>394</u>	294	194	3338
98	276	388	362	342	333	343	365	367	<u>321</u>	239	3337
99	349	484	426	365	313	286	284	293	287	<u>250</u>	3337
00	406	580	504	407	317	255	224	216	217	212	3337

assumed in this run, the population then begins to age rapidly as the stock level reaches above-equilibrium levels and recruitment drops off. This aging process continues until the mid-to-late 1980s, whereupon recruitment again rises since the stock levels have dropped below equilibrium and the younger year classes momentarily dominate and then begin to age as the process repeats itself, although this time with considerably less strength. It is interesting to compare the age distributions of 1978 and 1991 with those of 1984 and 1996. All these age distributions represent stock sizes of about 52,000 tons which is also in the vicinity of the eventual equilibrium stock level. However, the age distributions of 1978 and 1991 are much younger than those of 1984 and 1996, as might be expected, since the former are periods of peak biomass growth and the latter periods of peak biomass decline. Neither age distribution is representative of steady state and that is the reason for the overshoot.*

Table 5.3.1 exhibits one other phenomenon that is continually being observed in fisheries stocks which are out of equilibrium, and that is the "dominant year class." In Table 5.3.1 there are two dominant year classes. The first is the year class of 1978 generated by the first recruitment peak. This class dominates the catch of every year it is in the fishery except the first. Twelve years later there is another dominant year class, that of 1990, although since the fishery

*In order for a stock to be in equilibrium, it is not sufficient for the total biomass to be equal to the equilibrium level. Rather, each year class must be at equilibrium. Models which are based only on total population, such as the Schaefer formulation, overlook this point.

is slightly closer to equilibrium, this class's strength is somewhat reduced relative to that of 1978. A little reflection will reveal that in any fishery in which recruitment is varying as in Figure 5.3.2, the bulk of the fish caught will be those generated by the recruitment peaks. Any fishery which is out of equilibrium must necessarily be "carried" by a few peak year-classes. In Table 5.3.1, catches of the dominant year classes have been underlined.

These variations in age distributions are occurring despite a remarkably steady total catch. At this low level of effort, the catch is limited by the capacity of the few vessels fishing the stock rather than by the stock size. The point is that total catch is a very weak indicator of where one is in the cycle. The age distribution of the catch is much more revealing.

The obvious next question is: if the catch in Figure 5.3.2 is so stable, why are the fluctuations in Figure 5.3.2 with fishing so much more highly damped than those in Figure 5.3.1 without fishing? The answer lies in the difference between natural mortality and fishing mortality--at least in FISHDYN1's possibly inaccurate view. In FISHDYN1, natural mortality is based on numbers of fish. That is, each fish has an equal probability of dying in each year. Natural mortality is preferentially directed against the high numbers of fish year classes. Natural mortality affects total adult biomass only indirectly.

Fishing mortality, however, is based directly on mass. The CATCH routine first computes the total monthly catch in

mass terms and then apportions the total catch among the year classes on a mass basis. This implies that large fish have a greater chance of being caught than small fish. It also implies that fishing mortality is directed preferentially against the large biomass year classes. This is exactly what is required if a disequilibrium age distribution is to be brought into equilibrium, for under our assumptions it is biomass and not numbers which generates new recruitment. Conversely, if we were to use a CATCH routine in which each adult fish had the same likelihood of being caught, then the additional damping associated with fishing evident in a comparison of Figures 5.3.1 and 5.3.2 would not occur. Further, if we were to assume a CATCH model in which small fish were more likely to be caught than large--a real possibility in certain stocks due to the smaller fish's slower speed--then fishing effort would be destabilizing relative to no effort. In short, from a dynamic point of view, it can make a great deal of difference what one assumes about the age distribution of the catch versus the age distribution of the spawning population. We don't believe this point is fully appreciated in discussions of mesh size regulation. Large mesh is stabilizing; small mesh, destabilizing.*

*FISHDYN1 has the capability of modelling changes in mesh size by changing the age of initial exploitation. However, this capability was not exercised in these initial runs.

Under our catch assumptions, a further increase in effort further increases damping and also decreases the difference between the initial biomass and the equilibrium biomass. Figure 5.3.3 displays the results for 3,000 days of effort--twenty "standard vessels" full-time. For this level of effort the equilibrium biomass is about 42,000 tons and the system is within $\pm 4,000$ tons of this level by 1985. The phasing between the adult stock and recruitment is particularly clear in Figure 5.3.3. Note that the average recruitment is much higher with this level of effort than it was in Figure 5.3.2. The reduction in average biomass has moved us closer to the peak of the Ricker curve. One result is that the fishery is able to sustain a catch of about 7,000 tons, roughly double the catch in Figure 5.3.2.

A further increase in effort to 3,850 days fished per year results in the situation shown in Figure 5.3.4. For this level of effort, the initial biomass and the equilibrium biomass are almost the same. This, coupled with the damping effect of the now moderately heavy fishing, results in very little fluctuation in adult biomass. It also turns out that this level of adult biomass is very close to the peak on the Ricker curve. For the data we used, the peak actually occurs at 27,000 tons of biomass, at which point the recruitment two years later is 69 million fish. Hence, since the stock stabilizes at about 32,000 tons, recruitment stabilizes at a high level under the level of effort shown. This high level

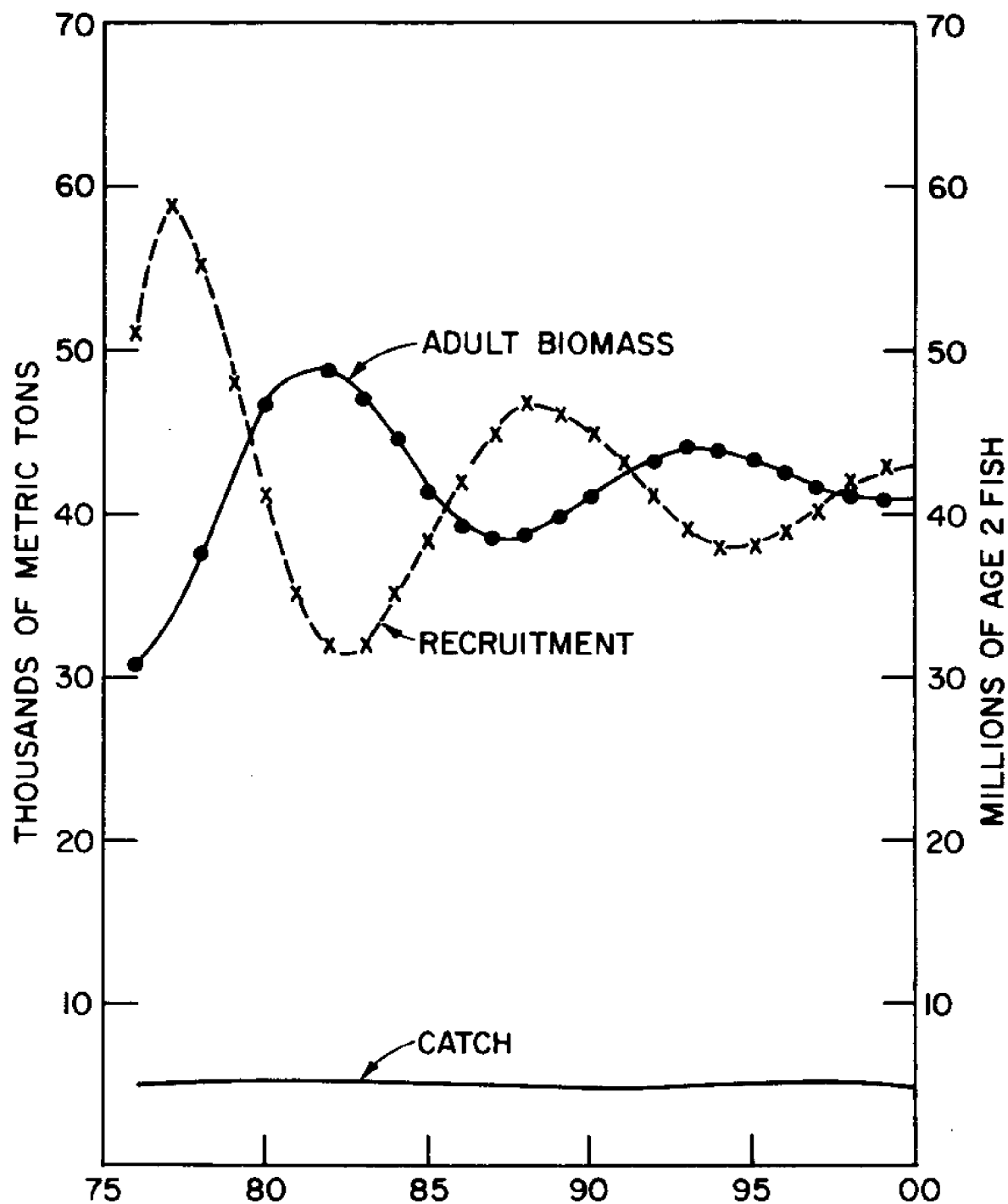


FIGURE 5.3.3 YELLOWTAIL FLOUNDER, 1976-2000 SIMULATION, DETERMINISTIC RICKER RECRUITMENT, 3000 DAYS EFFORT

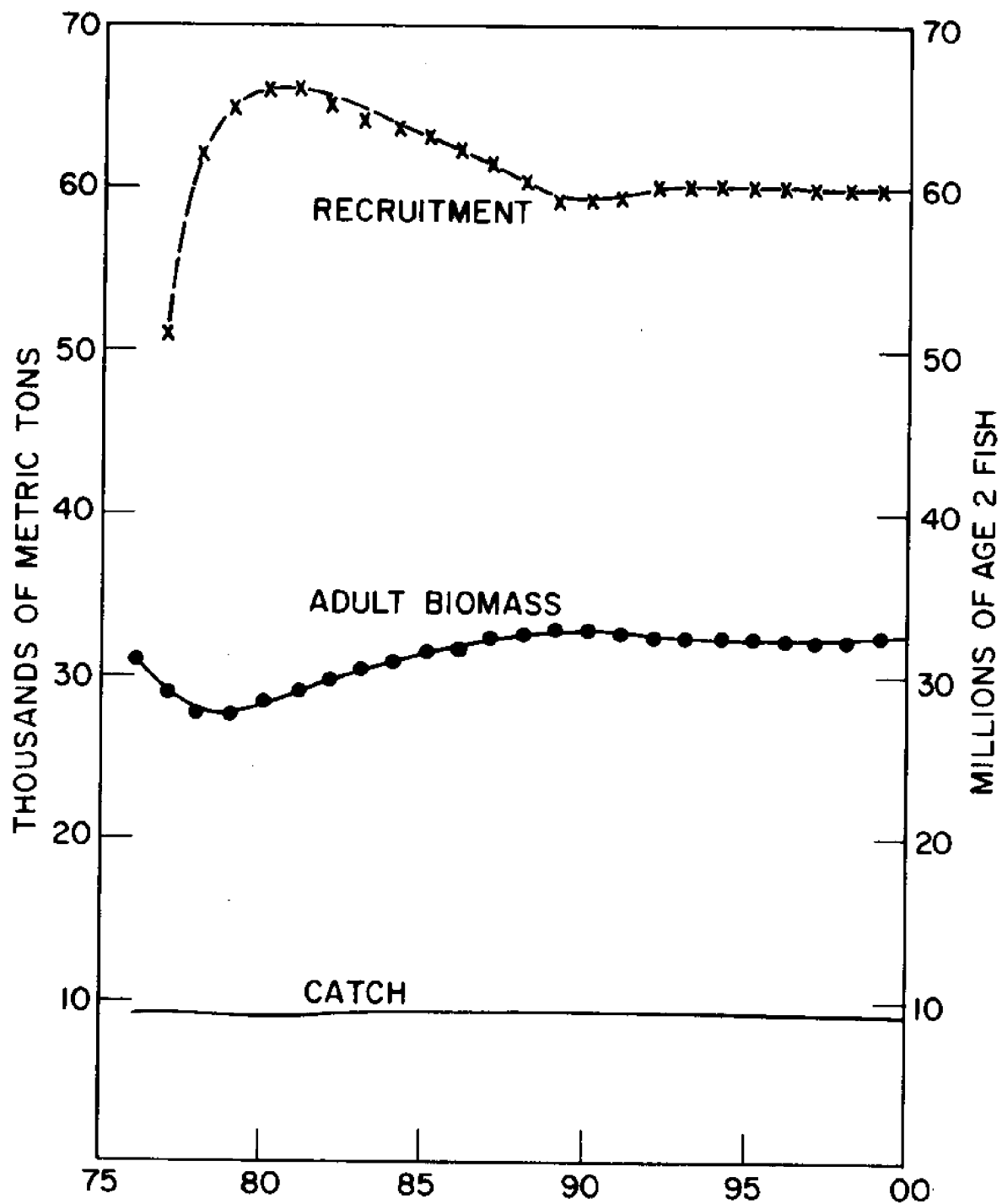


FIGURE 5.3.4 YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 3750 DAYS EFFORT,
27 'STANDARD VESSELS' FULL TIME,
MAXIMUM SUSTAINABLE YIELD LEVEL

of recruitment supports a catch of about 8,500 tons per year.

According to the model, this level of catch is just about the maximum sustainable yield under constant effort. For further increase in the level of effort of 150 days per year, a single vessel, results in the picture shown in Figure 5.3.5. Clearly, we have pushed the fishery into an entirely different behavioral mode. At this level of effort, recruitment, even at its highest level, is not quite able to keep up with the catch. The stock drops to about 27,000 tons where recruitment is at its peak. This high level of recruitment is almost but not quite able to hold the stock constant. As the stock level drops further, we slide onto the unstable portion of the Ricker curve, the portion below the peak. Below this peak, each further decrease in stock levels decreases recruitment, and the stock, and eventually the catch, begins an inexorable decline. By 1995, the catch and the stock consist almost entirely of newly recruited two-year-olds. It is interesting to note that the total catch holds up for a remarkably long time--declining almost imperceptably until the stock is in real trouble. This phenomenon has been pointed out by many fishery observers. Once again, total catch is a very poor indicator of the state of the stock.

Further increases in level of effort simply accentuate and speed up this behavior, as Figures 5.3.6, 5.3.7a and 5.3.8a reveal. The reason why the stock does not actually go to zero, despite the clearly excessive effort levels, is our

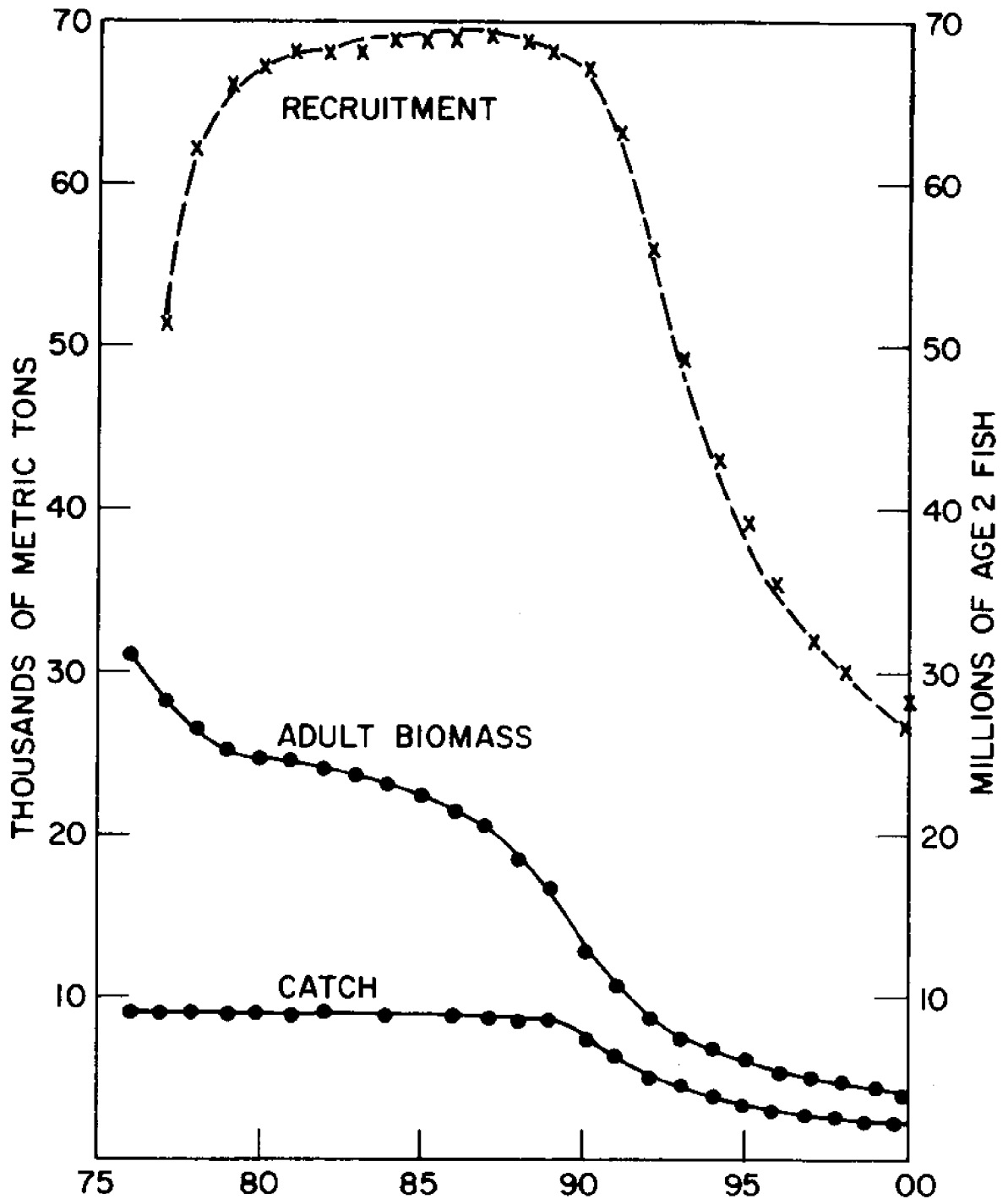


FIGURE 5.3.5 YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER FORM RECRUITMENT, 3900 DAYS
EFFORT, 28 'STANDARD VESSELS' FULL
TIME

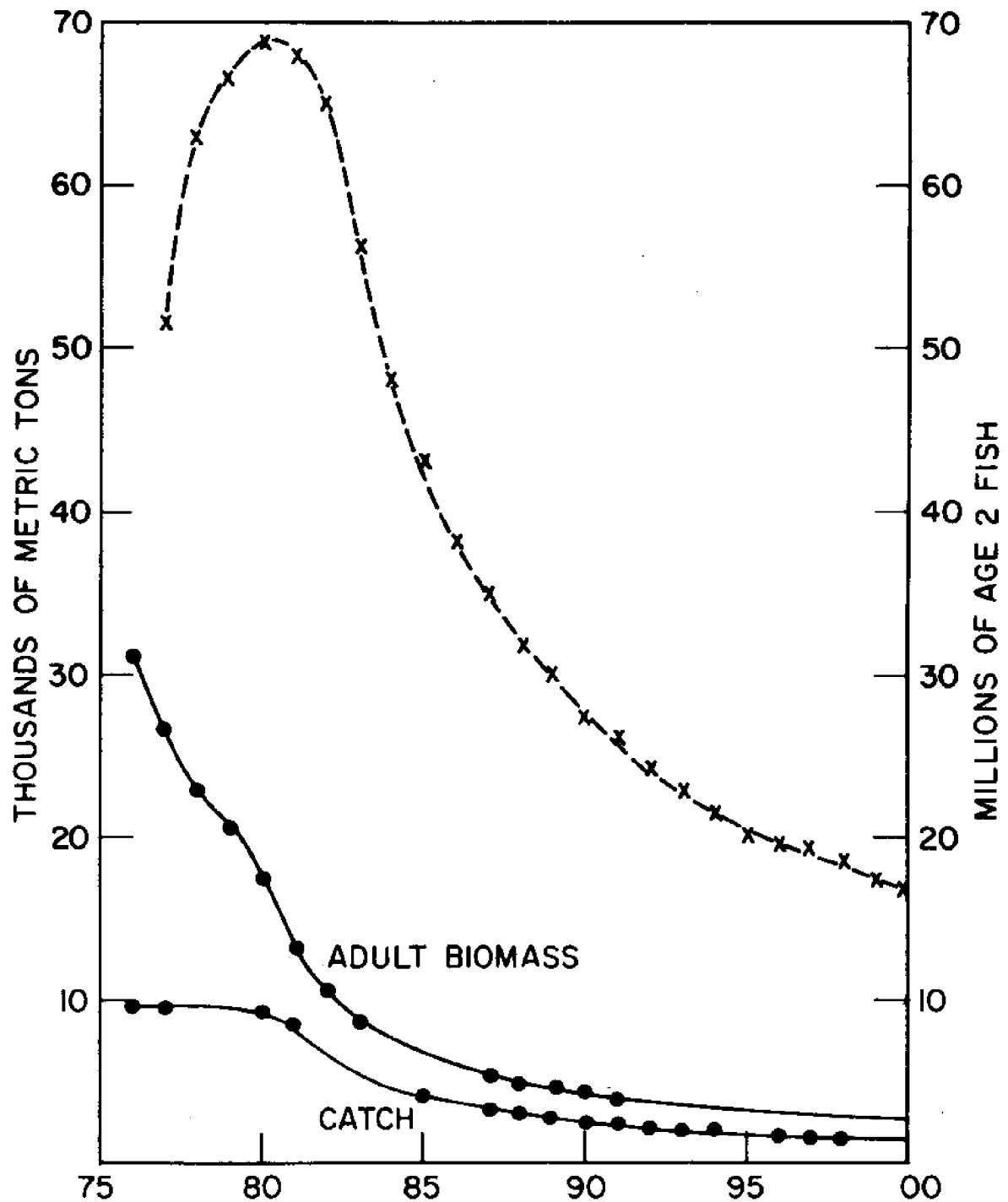


FIGURE 5.3.6 YELLOWTAIL FLOUNDER
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT 4500 DAYS EFFORT

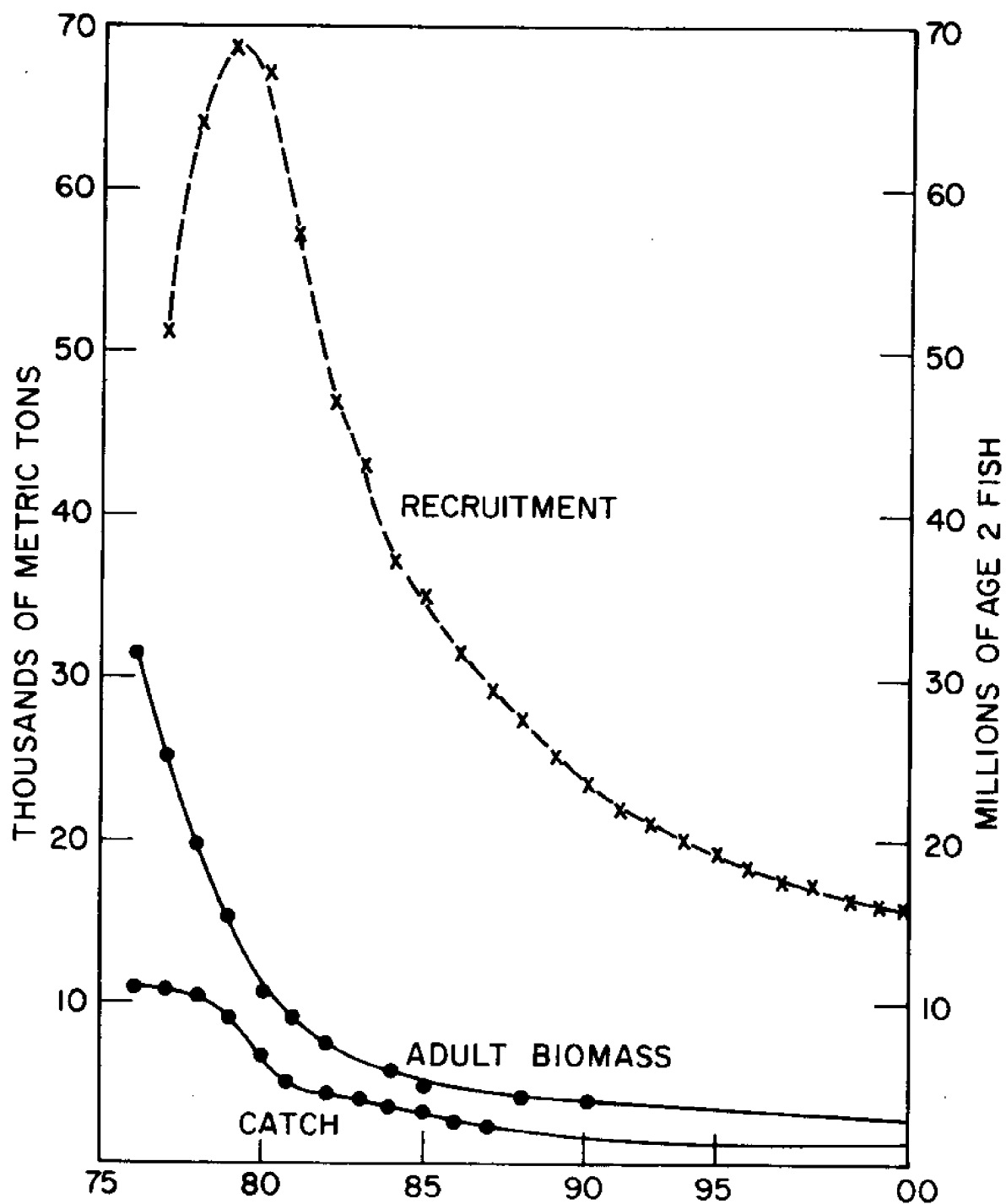


FIGURE 5.3.7a YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 6000 DAYS EFFORT
AVAILABLE 10,000 TON QUOTA

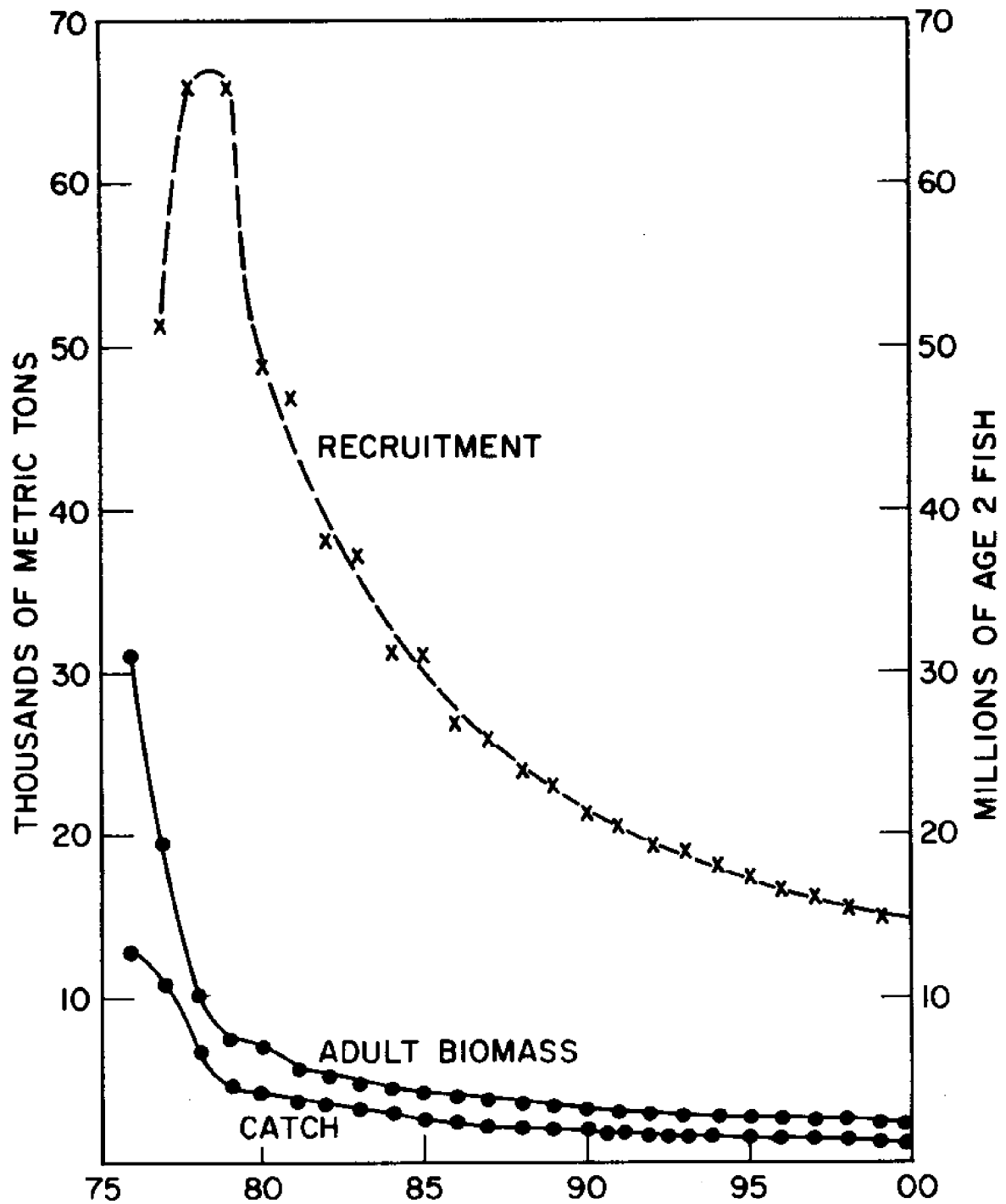


FIGURE 5.3.7b YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 6000 DAYS EFFORT,
UNLIMITED QUOTA

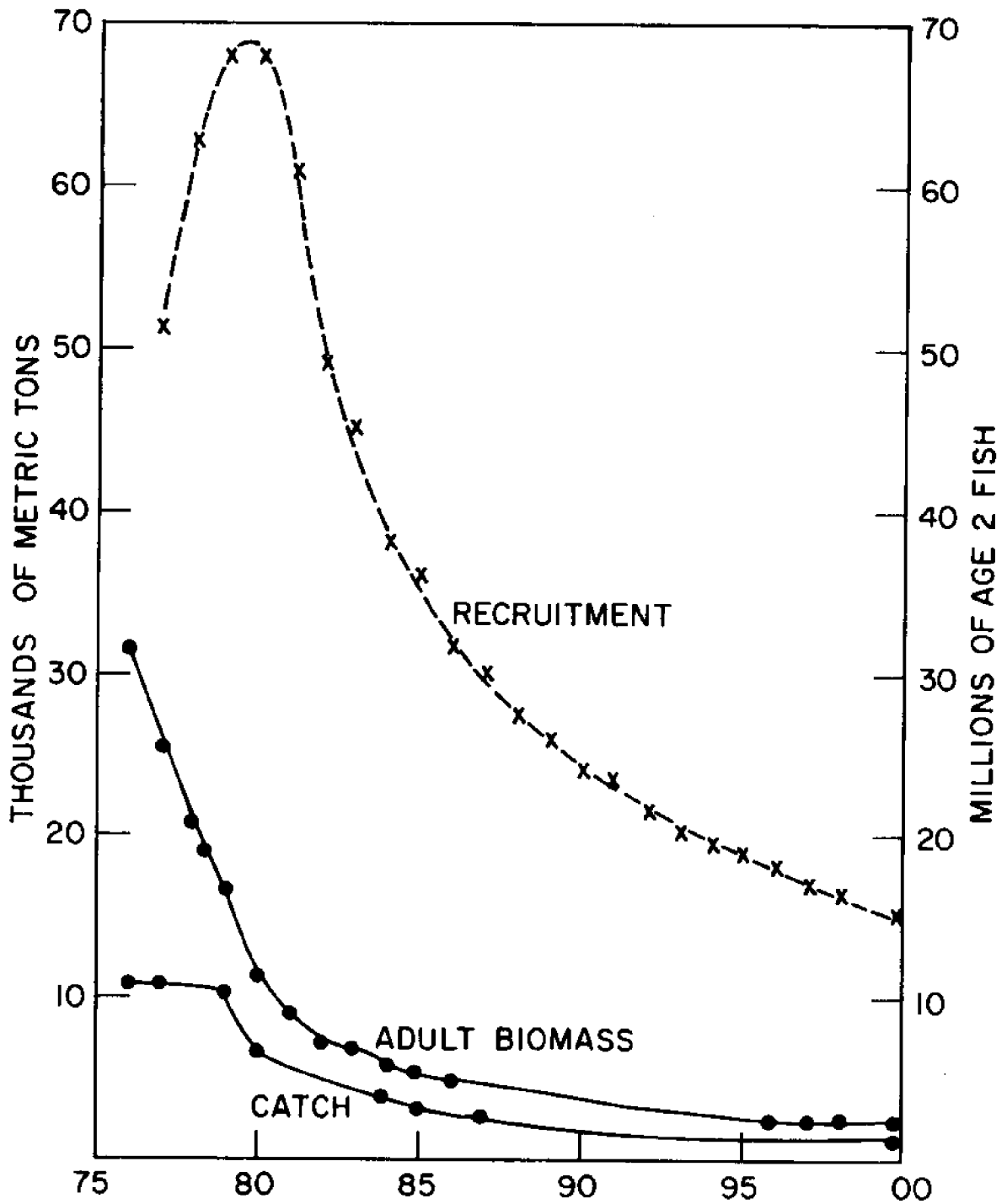


FIGURE 5.3.8a YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 7500 DAYS EFFORT
AVAILABLE, 10,000 TON QUOTA

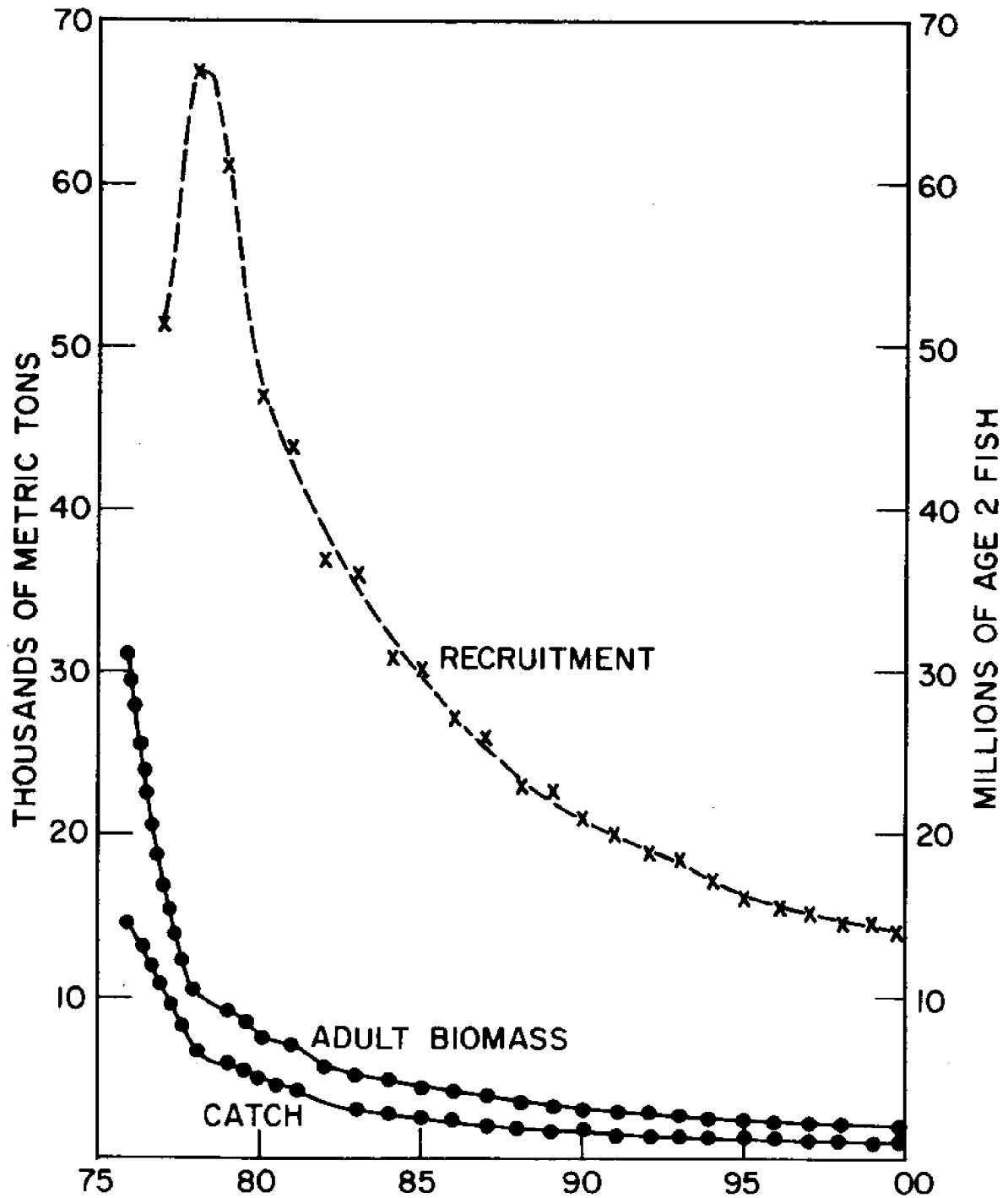


FIGURE 5.3.8 b YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 7500 DAYS EFFORT,
UNLIMITED QUOTA

assumption that the two-year-olds begin spawning at the same time as they enter the exploited stock. Hence, while the adult fishery consists almost entirely of newly recruited two-year-olds, some of these young fish to reproduce before they are caught. When the stock is at such low levels, even a small number of recruits can grow to an adult biomass which is equal to (or greater than if effort is reduced) the reduced spawning stock. Under the assumptions used in these runs, it is impossible to actually wipe the fishery out. Obviously, other possible assumptions--for example, newly recruited fish do not spawn until six months or a year after they begin to be exploited--would result in the fishery going to virtual extinction in those runs.

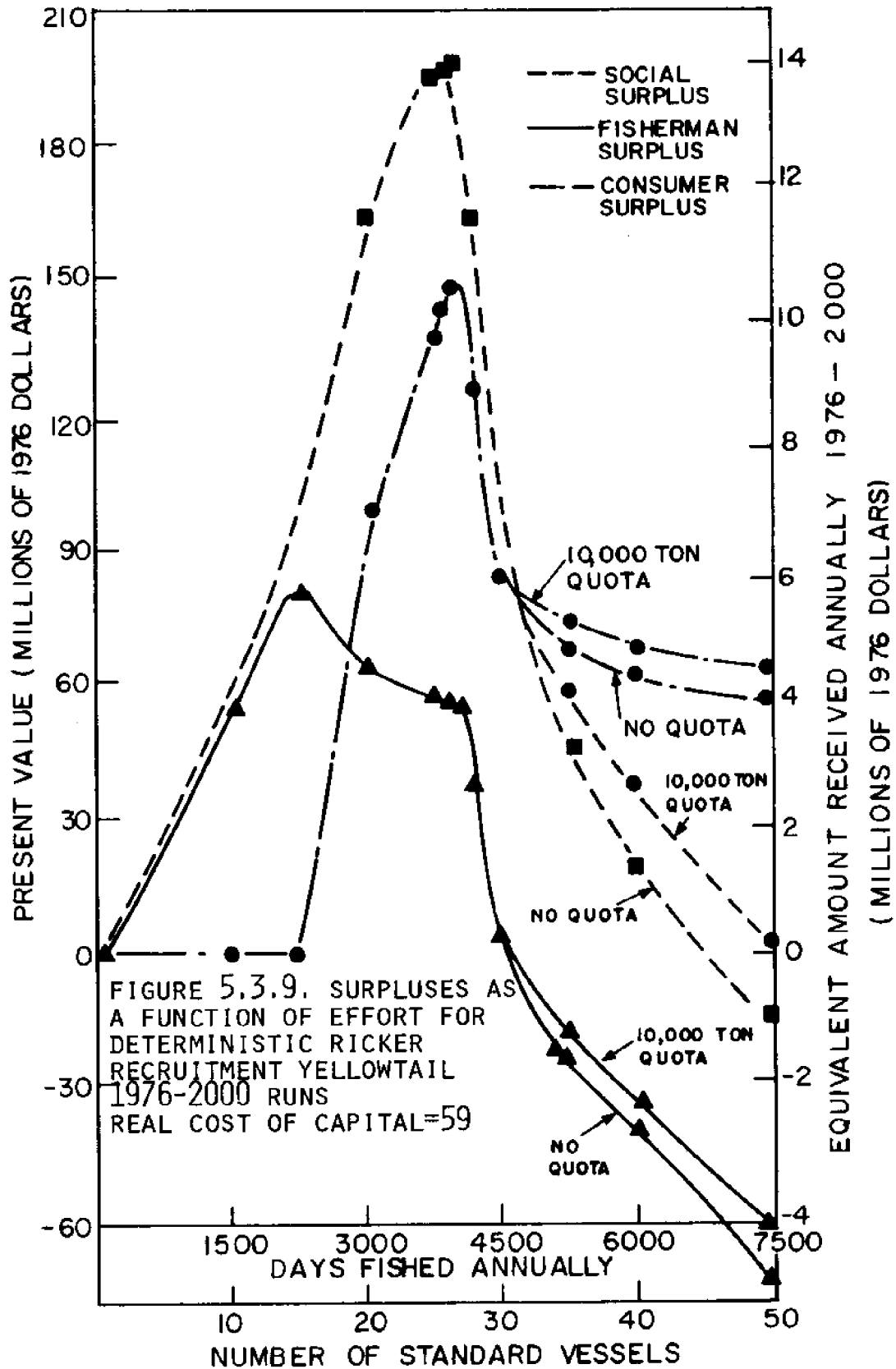
In recent years, the level of effort on the Georges Bank yellowtail stock has been estimated at 6,000 to 8,000 days fished. These estimates are subject to a rather large range of error, since vessels often fish more than one species on a single trip. National Marine Fisheries Service uses the criterion that if the catch was more than 50% yellowtail, the entire trip is deemed to be directed at yellowtail. If the catch is less than 50% yellowtail, then none of the trip is counted as yellowtail effort. This arbitrary dividing point is as reasonable as any, but it does leave us with considerable uncertainty as to how much effort has been going to yellowtail. Be that as it may, it is clear that if this model is at all descriptive of the real world and if the current effort is anywhere near what NMFS

estimates it to be, present effort is sufficient to push us onto the wrong side of the recruitment curve and then drive the stock to very low levels.

The overall economic results of the deterministic Ricker recruitment runs are summarized in Table 5.3.2 and displayed in Figure 5.3.9. Qualitatively, these results are rather similar to those for the fixed recruitment runs, Figure 5.2.2. However, the peaks and valleys are more pronounced. If the stock is managed correctly, then higher surplus can be obtained. This is because we are operating near the peak of the Ricker recruitment curve and obtaining above-average recruitments. By the same token, the penalty for overexploitation is much higher. Above about 4,000 days effort, we are operating on the wrong side of the recruitment peak and will obtain, at least eventually, much lower than average recruitments. Perhaps the most striking point about this figure is the narrowness of the peaks. In order to obtain near-maximal social surplus from the fishing, effort must be controlled within ± 300 days of 3,600 days effort. This is a range of only four "standard" vessels. Moreover, the buyer-seller conflict between the fisherman and the fish purchaser is definitely of secondary importance. Both groups get hurt, and drastically hurt, by overexploitation, especially the fishermen. The drop-off in both consumer and fisherman surplus at about 4,000 days effort is especially startling. Prudence would dictate a somewhat lower level, even from the consumer's point of view, at which point we wouldn't really be that far from the fisherman's optimum.

TABLE 5.3.2
SOCIAL SURPLUS, FISHERMAN SURPLUS, AND CONSUMER SURPLUS VERSUS FISHING EFFORT FOR
DETERMINISTIC RICKER RECRUITMENT, YELLOWTAIL SIMULATIONS, 1976-2000 (PRESENT VALUE IN
MILLIONS OF 1976 DOLLARS)

Fishing Effort (Days Fished) Annually	10,000 Ton Quota			Unlimited Quota		
	Fisherman Surplus	Consumer Surplus	Social Surplus	Fisherman Surplus	Consumer Surplus	Social Surplus
0	0.0	0.0	0.0	0.0	0.0	0.0
1,500	55.1	0.0	55.1	55.1	0.0	55.1
2,250	82.4	0.0	82.4			
3,000	64.7	98.9	163.6	64.7	98.9	163.6
3,750	58.0	138.3	196.4	58.0	138.3	196.4
3,900	56.6	144.3	200.9			
4,050	55.2	149.7	204.9			
4,200	38.6	126.2	164.8			
4,500	5.3	84.2	39.5	5.3	84.2	39.5
5,250	-17.9	74.7	56.8	-21.6	68.4	46.8
6,000	-34.9	70.9	36.0			
7,500	-63.0	68.5	5.5	-71.4	58.5	-12.9



Examination of the foregoing results will reveal that a constant 10,000 ton quota, the current Regional Council-set level, has very little effect on the fishery relative to no quota at all. Below about 5,000 days effort, a 10,000 ton quota is never operative because the fleet can't catch 10,000 tons under our assumptions. All the results, biological and economic, are exactly the same with and without the 10,000 ton quota. Above 5,000 days effort, a 10,000 ton quota is not restrictive enough to keep the stock from moving to the wrong side of the Ricker curve and subsequently entering a steep decline. After it enters this decline, once again, the quota is inoperative. According to our results, the only effect of a 10,000 ton quota will be to slightly delay the stock decline for moderately heavy ($\sim 5,250$ days effort) levels of effort. At current levels of effort available ($\sim 7,500$ days), the amount of this delay is almost negligible. If the model is correct, a 10,000 ton quota is almost no quota at all. The runs also indicate that a catch of about 8,000 tons is about the maximum sustainable under constant effort available. Hence, it is interesting to examine what would happen if a quota of 8,000 tons were imposed, but effort was not limited. The results for 6,000 days effort available are shown in Figure 5.3.10.

Biologically, the results are not bad at all. The biomass stabilizes around 35,000 tons, and total landings over the period rank up with the best of the limited-effort strategies.*

*Actual landings stabilize at about 8,700 per year, for in FISHDYN1, the enforcement of a quota is lagged one month. That is, fishing is allowed to proceed through the month in which the quota is reached. This is why the 1976 through 1978 landings in Figures 5.3.7a and 5.3.8a are slightly above 10,000 tons

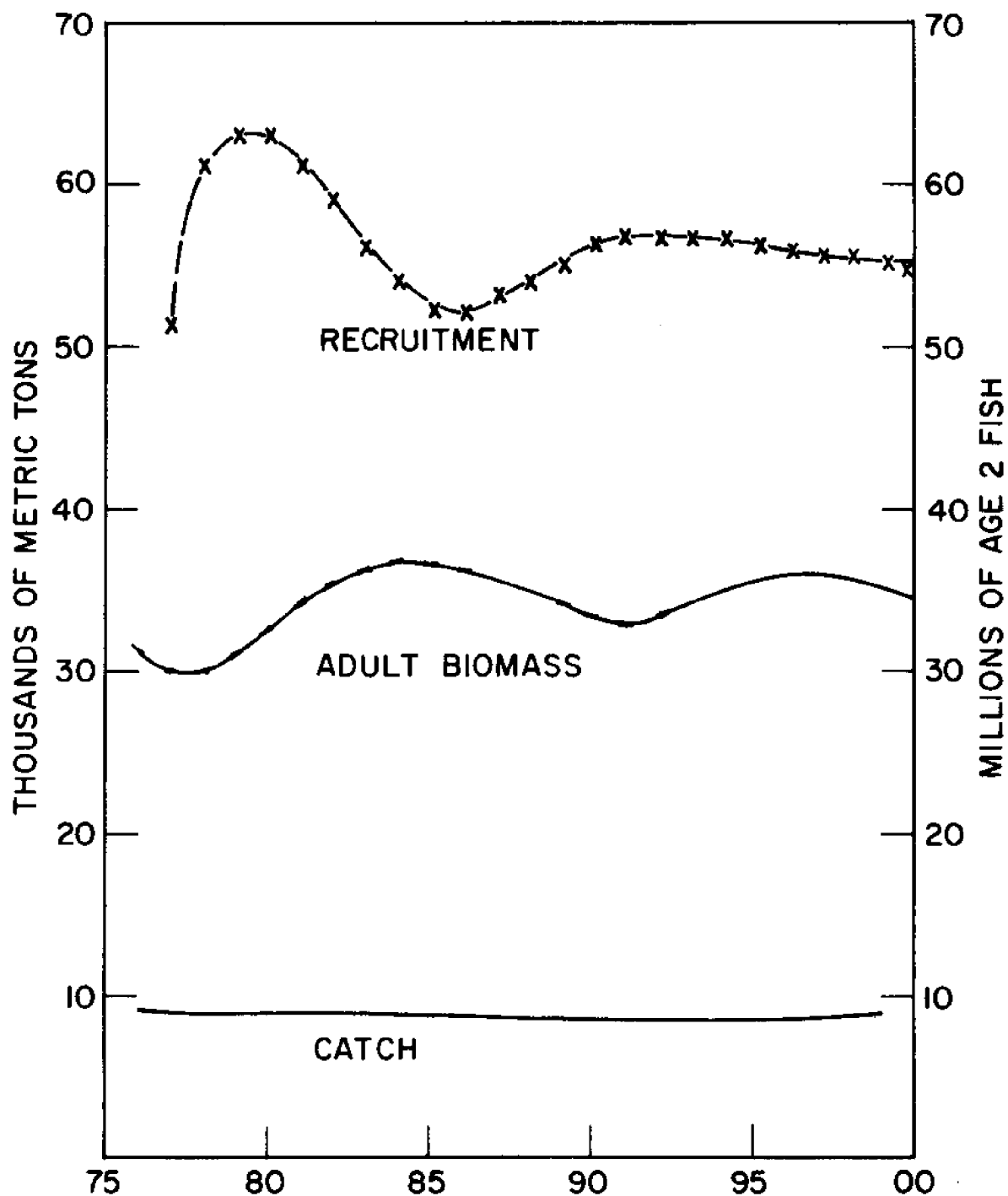


FIGURE 5.3.10 YELLOWTAIL FLOUNDER,
1976-2000 SIMULATION, DETERMINISTIC
RICKER RECRUITMENT, 8000 TON QUOTA,
6000 DAYS ANNUAL EFFORT AVAILABLE

If you're going to have a quota, this is clearly a near-optimal one. A quota of 9,000 puts the fishery into decline.

However, despite the excellent biological results, the economic results leave something to be desired. Table 5.3.3 compares the surpluses associated with the optimal limited-effort simulation against the optimal quota plan with 6,000 days effort available.

The consumer loses a little bit as a result of the quota relative to the optimal limited-effort strategy investigated, despite the fact that total landings are about equal. This is because the quota is caught all in the first eight months of the year and he must do without fresh yellowtail the remainder of the year. The decrease in prices in the early part of the year is not sufficient to make up for the loss of consumer surplus in the remainder of the year.* But the real loser is the fisherman. Under the quota system, with 6,000 days effort available, he is just barely breaking even. Hence, this level of effort is close to the Free Entry point with this quota. The fishermen as a group are forgoing about \$4 million per year in net income obtainable if they could somehow reach an agreement to reduce the level of effort available from 6,000 days to about 4,000 days. The fishermen are burned in two ways by the quota as opposed to effort

*Since we have assumed the same monthly demand curve throughout the year, this is a product of the convexity of the demand curve in Figure 4.4.1. If we had assumed a linear demand curve, the consumer's surplus associated with bunching the landings would be the same as more evenly distributed landings, indicating the consumer is indifferent between consuming a lot at once at low prices or the same amount spread out over the year at higher prices. A concave demand curve would imply the consumer actually prefers the bunched landings. These implications would seem to argue for demand curves shaped as in Figure 4.4.1.

TABLE 5.3.3
LIMITED EFFORT VERSUS OPTIMAL QUOTA PRESENT-VALUED SURPLUSES (MILLIONS OF 1976 DOLLARS)

	Optimal Limited Effort	Optimal Quota Assuming Effort Available Stabilizes at Long-Run Free-Entry Point
Fisherman surplus	55.2	3.9
Fish purchaser surplus	149.3	132.1
Social surplus	204.9	136.0

limitation. First, there is the cost of running 50% or more too many vessels. Secondly, all the fish are landed in the early months of the year, depressing prices and hence revenues. No fish are landed in the last four months of the year when, under the quota, such landings would command extremely high prices.* The differential in social surplus between the two schemes is a measure of the total loss in national income (about \$5 million per year over the twenty-five-year period) associated with opting for the "optimal" quota scheme versus the optimal limited-effort scheme under the assumptions used in these runs. By the same token, the optimal quota scheme is some \$90 million better than no regulation at all--which is what, for all practical purposes, we may well have if the current 10,000-ton quota prevails.

5.4 Results of stochastic simulation of recruitment based on Bayesian regression of 1963-1975 yellowtail data

Table 5.4.1 summarizes the results of the Mode C recruitment runs. It is extremely important to re-emphasize that each line in Table 5.4.1 represents twenty complete runs. In each of these individual runs, the recruitment in each year was obtained by random sampling from the recruitment density corresponding to the current biomass. This density in turn was obtained by the Bayesian methods outlined in Section 4.5.3. In total, then, Table 5.4.1 represents 200 different simulations of the 1976-2000 period. For example, consider Figures 5.4.1 and 5.4.2. These figures represent

*Attempts to spread the no-landings periods throughout the year by imposing quarterly quotas really don't address the problem because of the perishability of the commodity. In the New England fresh fish markets, it only takes a week or two of no landings to send prices to extremely high levels.

TABLE 5.4.1
OVERALL STATISTICS OF STOCHASTIC SIMULATIONS. GEORGES BANK YELLOWTAIL FLOUNDER, 1976-2000. ANNUAL QUOTA = 10,000 TONS.^a
COST OF CAPITAL = 5%.

Level of Effort (Days)	No. of Samples	Fisherman Surplus				Consumer Surplus				Social Surplus			
		Sample Mean	Sample Std Dev	Sample Min	Sample Max	Sample Mean	Sample Std Dev	Sample Min	Sample Max	Sample Mean	Sample Std Dev	Sample Min	Sample Max
1500	20	55.1	0.0	55.1	55.1	0.0	0.0	0.0	0.0	55.1	0.0	55.1	55.1
3000	20	64.7	0.1	64.7	64.7	98.9	0.2	98.8	99.0	163.6	0.3	163.5	163.7
3750	20	58.0	0.1	57.9	58.0	138.3	0.3	138.0	138.5	196.3	0.4	195.8	196.6
3900	20	56.1	2.1	46.8	56.7	143.1	4.6	123.2	144.5	199.3	6.7	170.0	201.2
4050	20	48.4	11.6	20.1	55.3	137.6	20.1	91.7	150.0	186.0	31.8	111.9	205.4
4200	20	43.4	13.9	16.1	53.9	135.9	24.6	90.0	155.0	179.2	38.5	108.3	208.9
4500	20	21.9	16.6	-2.6	50.3	112.3	27.9	74.1	162.4	134.2	44.5	71.5	212.7
5250	20	-15.1	5.7	-25.1	-1.6	79.3	8.6	64.8	101.7	64.2	14.3	39.7	100.1
6000	20	-30.7	7.8	-41.1	-14.7	78.0	11.8	63.1	104.1	47.3	19.7	32.5	89.3
7500	20	-57.4	8.1	-73.3	-36.5	77.5	11.9	54.3	108.5	20.1	20.0	-19.0	71.9

^aCatch limited by quota only for level of effort available in excess of 5,000 days, and then only in 1976 to 1980 period in most runs.

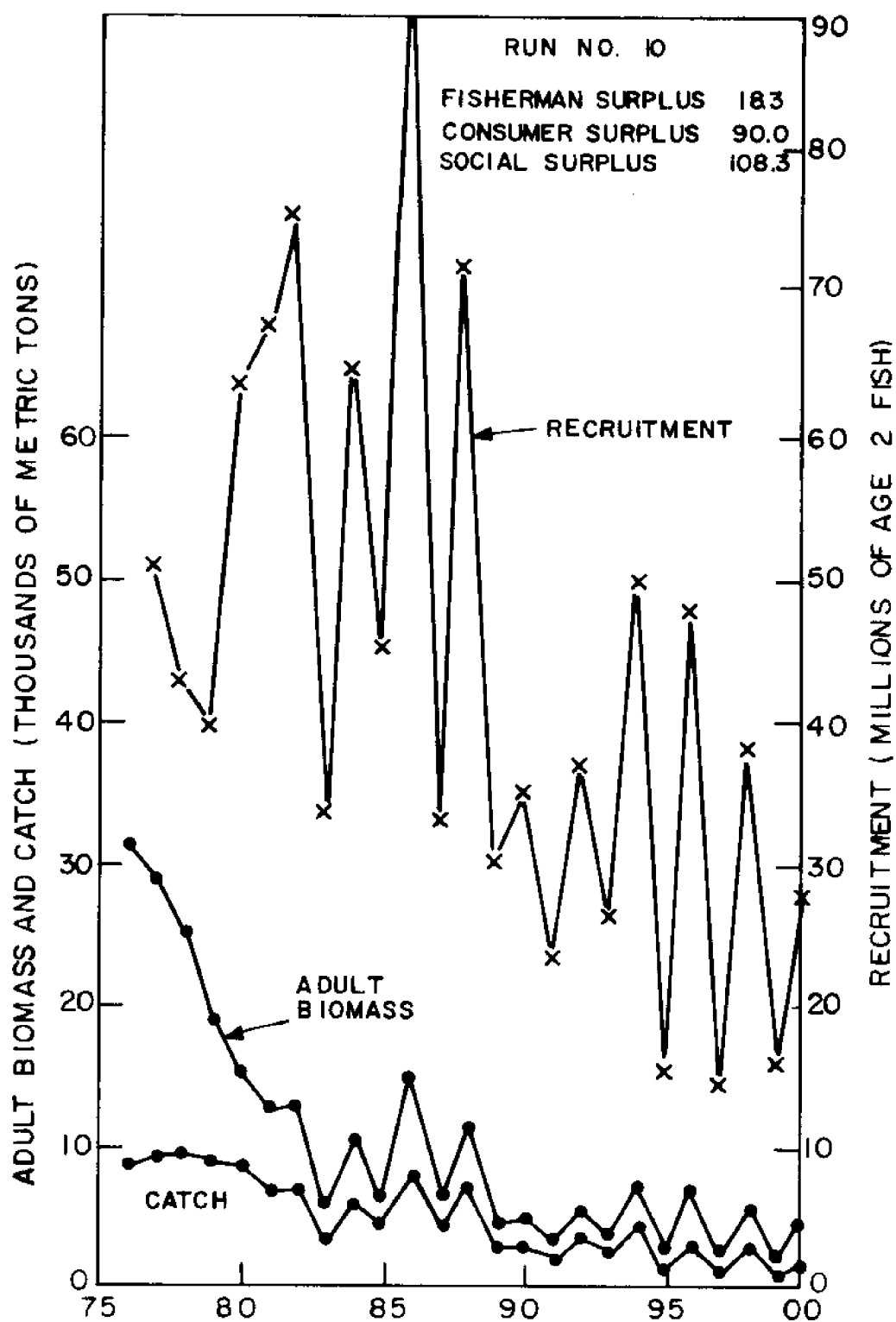


FIGURE 5.4.1 RUN NO. 10, STOCHASTIC YELLOW-TAIL SIMULATION, 4200 DAYS EFFORT

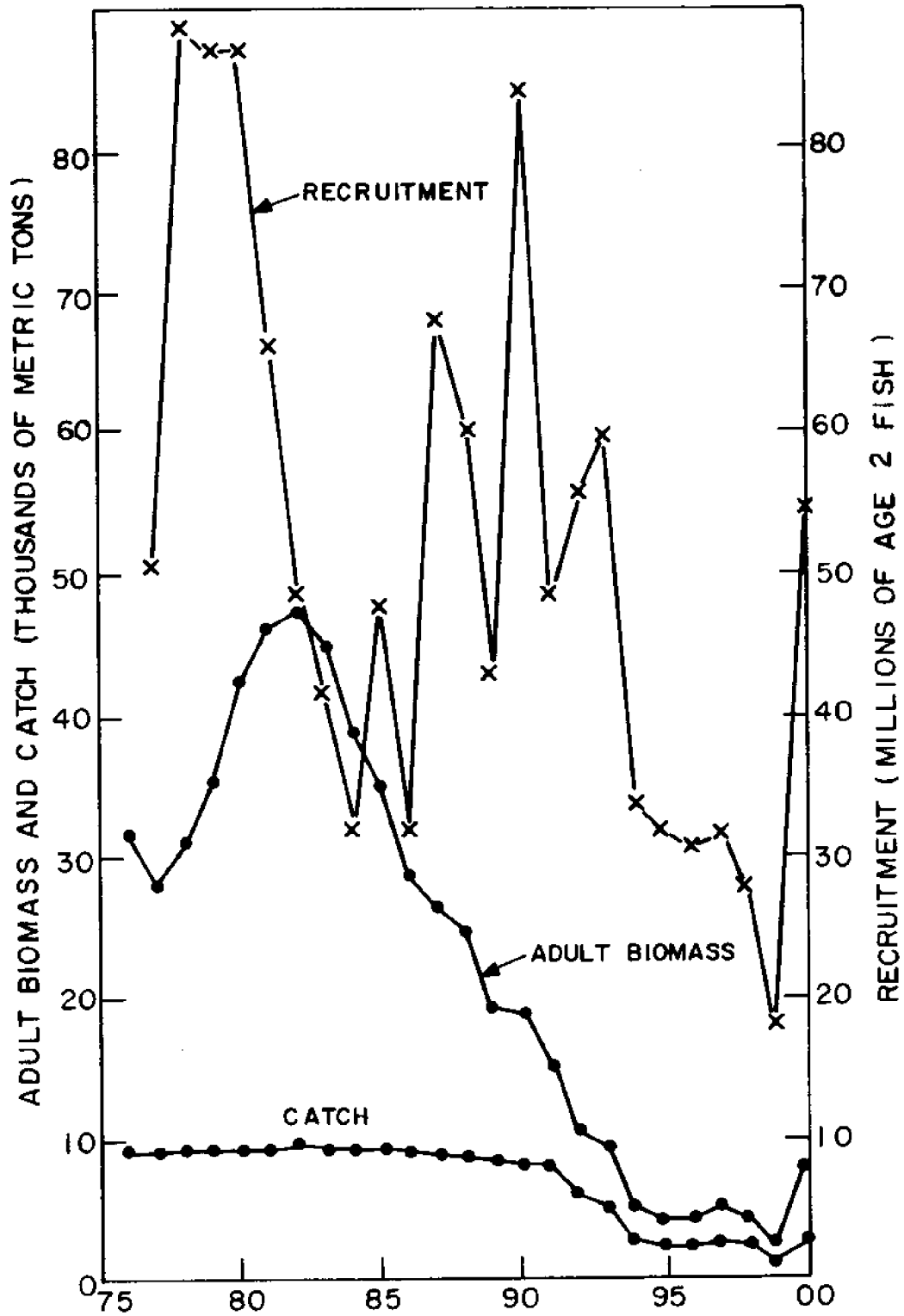


FIGURE 5.4.2 RUN NO. 20, STOCHASTIC YELLOWTAIL SIMULATION, 4200 DAYS EFFORT

two of the individual runs (Runs No. 10 and 20) for the twenty-eight-vessel, 4,200-day level of effort. In Run No. 10, the fishery was quite unfortunate in obtaining considerably less than the average recruitment for the corresponding biomass in the late 1970s and early 1980s. As a result, the stock was pushed onto the wrong side of the Ricker curve almost immediately and, under the higher-than-optimal level of effort assumed, was unable to recover despite occasionally much higher-than-average recruitment thereafter. In Run No. 20, on the other hand, the stock was blessed with three years of much higher-than-expected levels of recruitment in the late 1970s and hence, despite the higher-than-optimal level of effort, was not pushed onto the wrong side of the Ricker curve and into decline until the late 1980s. Note that once the system gets pushed to the wrong side of the Ricker curve, both recruitment and biomass can exhibit a strong two-year periodicity. This results from the fact that the adult biomass is eventually made up almost entirely of newly recruited two-year-olds who are caught in the same year they are recruited. It's almost as if we have two stocks, the odd-year stock and the even-year stock--a sort of artificially generated salmon fishery. In terms of social surplus, Run No. 10, at \$108.3 million, turns out to be the worst of the twenty samples at this level of effort. Run No. 20, at \$170.9 million, turns out to be slightly worse than the average of the twenty samples, which is \$197.2. In six out of the

twenty runs, recruitment was high enough that the fishery stayed on the right side of the Ricker curve through the entire twenty-five-year period, resulting in a present-valued social surplus of about \$208 million. Figure 4.5.3 displays a histogram of the social surpluses for the entire twenty runs for this level of effort.

It would be extremely unwieldy to attempt to work with the individual results of 200 samples. Hence, in Table 5.4.1 we have displayed some overall statistics of each set of samples, including the sample average and the sample standard deviation. However, in using this data, we caution that the numbers shown are merely sample statistics and not the "real values." In particular, the sample minimum and sample maximum is not the minimum (maximum) possible social surplus obtainable for a given level of effort, but merely the smallest (largest) value observed in twenty samples. Similarly, the sample mean is not the actual mean--an inherently unobservable entity--but only an estimate of the actual mean.*

These caveats notwithstanding, it is of interest to compare the results of Table 5.4.1, the stochastic simulations, with those of Table 5.3.2 for the deterministic run.

Remember the only difference between these two sets of runs

*Since the form of the social surplus density is not known and given its highly non-Normal character, it's a little difficult to say just how good an estimate this sample average is. Perhaps the simplest approach would be an empirical one. That is, repeat the twenty-sample process, say, ten times and observe the variation in the sample averages.

is that in Table 5.4.1, our uncertainty as to the values of the parameters in the Ricker form has been incorporated in the model. Everything else is the same. In particular, both sets of runs assume Ricker-form recruitment. Figure 5.4.3a makes this comparison in terms of social surplus for the 10,000 ton quota runs; Figure 5.4.3b, for the unlimited quota runs.

Below about 3,750 days effort, there is essentially no difference in the overall economic results between the deterministic and stochastic runs. At the lower levels of effort, the catch is limited by the number of vessels operating and not by the biomass. The stock always stays safely in the stable portion of the recruitment curve. Hence, random variations in recruitment have no effect on landings. Thus, at lower levels of effort the mean of the stochastic runs is almost exactly the same as the results for the deterministic runs and there is little or no sample-to-sample variation. This is true not only of the total social surplus but of the fisherman and fish purchaser surplus as well, as can be seen by inspection of Table 5.1.1.

However, as we approach the optimal level of effort, in the vicinity of 4,000 days effort, several interesting things occur. One is that there is considerable sample-to-sample variation in the stochastic results. Luck in recruitment is now critical to how long the stock stays on the right side of the peak in the Ricker recruitment curve. As a result, at 4,500 days effort, the twenty-sample range of variation is of the same order of magnitude as the twenty-sample mean. Below 3,900 days effort, the deterministic result is slightly

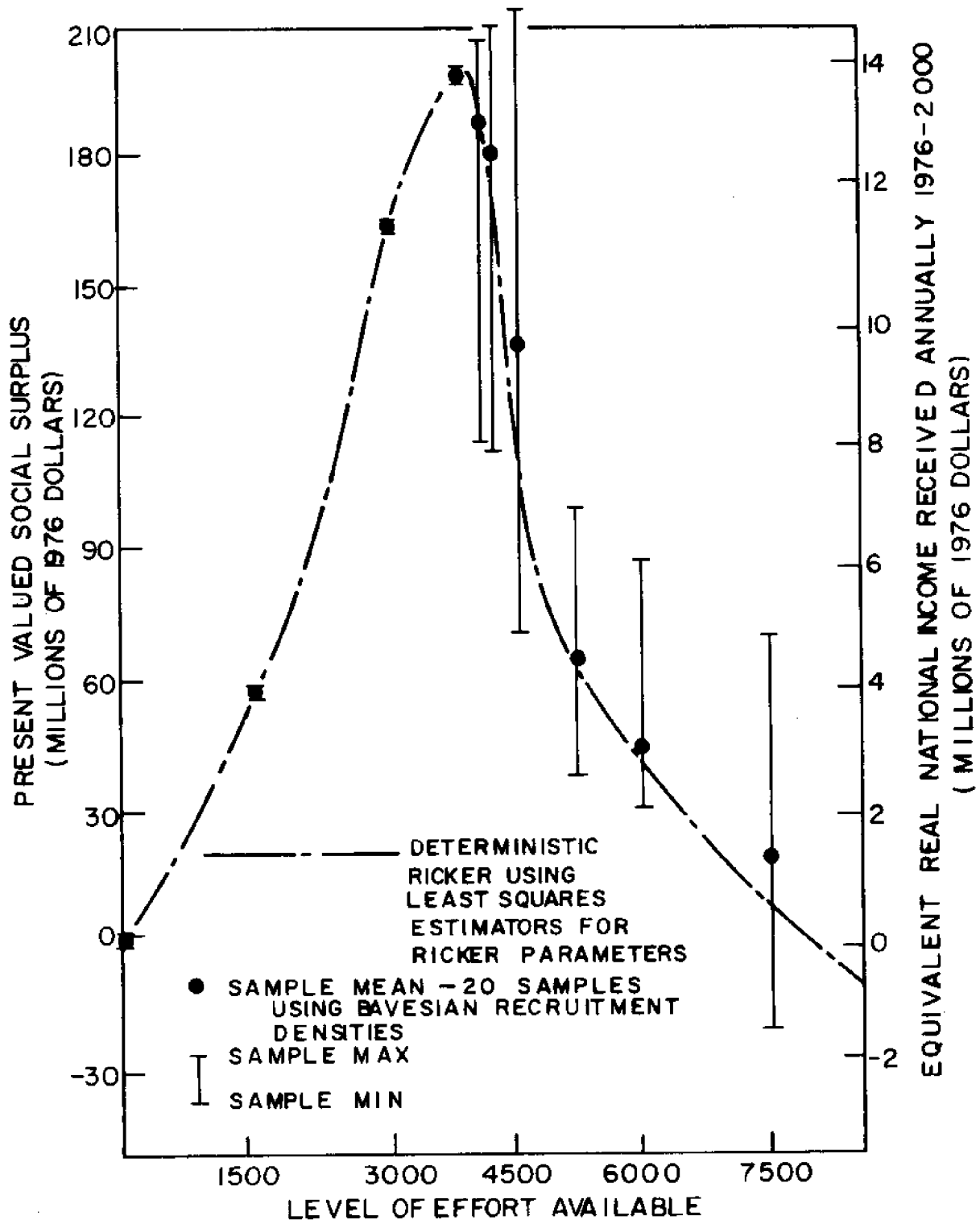


FIGURE 5.4.3. a COMPARISON OF SOCIAL SURPLUS
GENERATED BY DETERMINISTIC RICKER
RECRUITMENT WITH STATISTICS OF
STOCHASTIC RICKER RUNS, 10,000
TON QUOTA

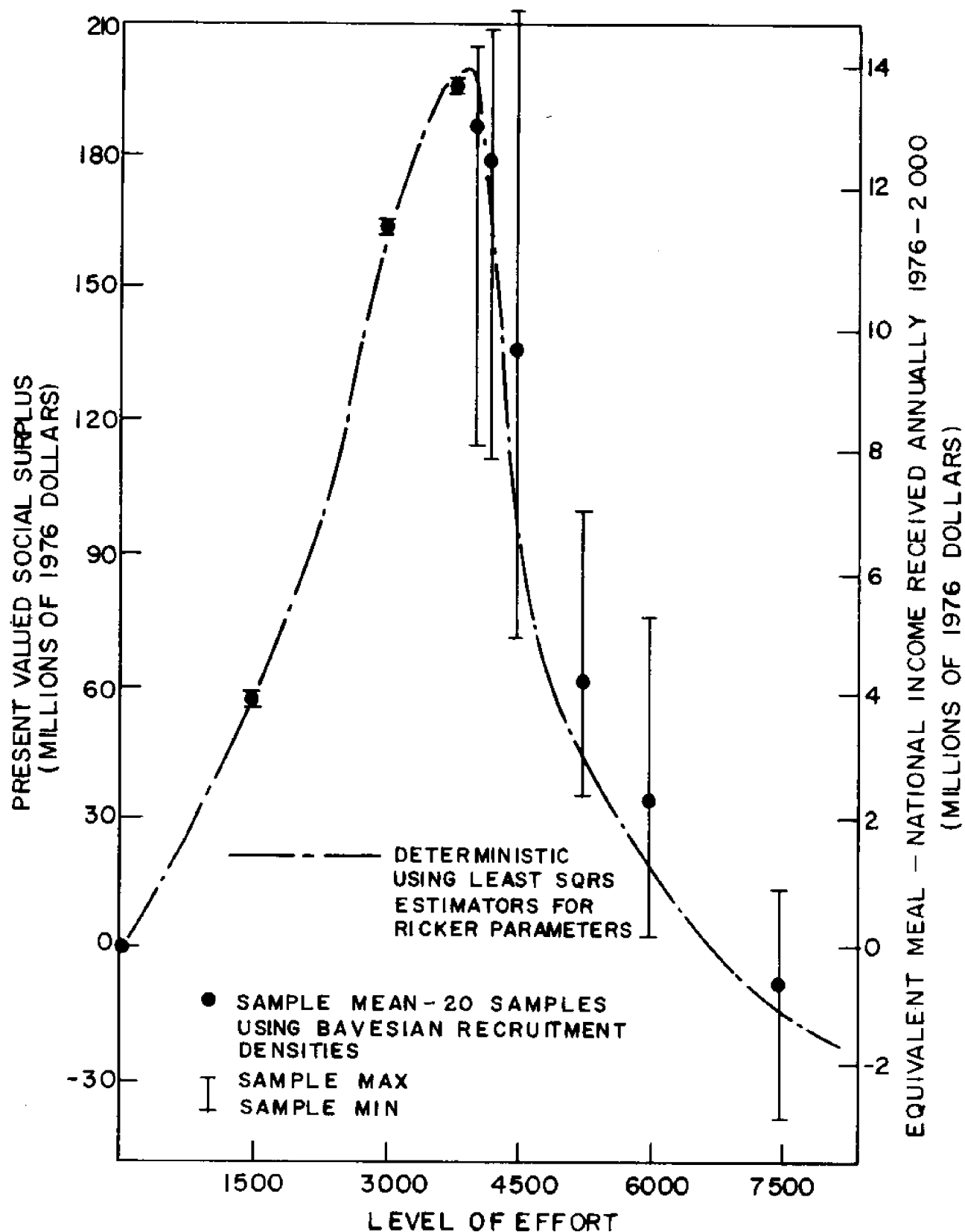


FIGURE 5.4.3b COMPARISON OF SOCIAL SURPLUS GENERATED BY DETERMINISTIC RICKER RECRUITMENT RUNS WITH STATISTICS OF STOCHASTIC RICKER RUNS, NO QUOTA

higher than the mean of the stochastic results. Below 3,900 days in the deterministic run, the stock always remains above the peak in the Ricker curve, but in the stochastic runs it is possible to be unlucky in recruitment and end up on the wrong side of the peak with subsequent stock decline. Above about 4,200 days effort the reverse is true. Under deterministic recruitment, we are certain of sending the stock into decline. However, under stochastic recruitment there's a chance we'll get lucky, obtain high recruitment, and stay above the peak longer, or, if we do go onto the wrong side of the peak, there's a chance we'll get very lucky and obtain a high enough recruitment to put us back on the right side of the peak. Hence, if you're an inveterate gambler you might be willing to push the stock a little harder under stochastic recruitment than under deterministic recruitment.* On the other hand, if you're very risk-averse, worried about the downside possibilities, then you would order less effort under stochastic recruitment than under deterministic.

Perhaps the most striking result of Figures 5.4.3a and b is that the deterministic and stochastic runs are not all that different, at least from the point of view of management

*Actually, the chances of getting away with this are better than they appear in Figures 5.4.3a and b. The skewness of the social surplus density implies that the probability of obtaining higher than the mean is a good deal better than .5. In fact, the mode of this density appears to be rather close to the sample maximum, at least up to about 4,200 days effort.

implications. Both claim a 10,000 ton quota is little better than no quota at all. Both point to an optimal level of effort in the vicinity of 3,500-4,000 days.* Both indicate that the near-optimal range of levels of effort is quite narrow. And both indicate, as can be seen in Table 5.1.1, that the buyer-seller conflict between the fisherman and fish purchaser is of a very secondary nature compared to the possible variations in the overall size of the economic pie. Another indication of this is the lack of negative correlation between fisherman surplus and consumer surplus for a given level of effort. Inspection of Table 5.4.1 will reveal that the standard deviation of the social surplus is almost exactly equal to the sum of the standard deviations of the fisherman surplus and consumer surplus. For a given level of effort, bad luck for the fisherman is also bad luck for the consumer, and vice versa. In short, all our insights from the deterministic runs appear to carry over into the stochastic case with remarkably little change. This is a result that the authors, at least, would never have predicted--at least not at near-optimal levels of effort.

*As did, surprisingly enough, the fixed recruitment runs.

CHAPTER 6

SUMMARY

6.1 The methodological level

As mentioned at the beginning, this effort can be viewed on two levels:

- a. as an exercise in modelling technique;
- b. as an attempt to speak to the immediate management problem facing the New England Regional Council with respect to the yellowtail flounder.

On the methodological level, a number of rather definite conclusions can be drawn.

1. The necessity of disequilibrium, dynamic analysis.--

We believe that in total, the results of this effort add another voice to the rising chorus of analyses which indicate that steady-state fisheries models can lead not only to quantitatively inaccurate but also to qualitatively misleading results. The yellowtail appears to be one more example of a stock whose current population distribution is in a strongly disequilibrium state for just about any level of effort, and for whom restoring forces are weak and lagged, leading to the possibility of large-amplitude, lightly damped fluctuations. Such a system has no strongly stable steady state, especially in view of the likely perturbations imposed on it by nature. With today's computational power, there is simply no excuse for feeling constrained to steady-state models in such situations.

At the same time, it is not enough to simply "go dynamic." We have seen that rather subtle changes in assumptions can have a very large effect on the dynamic characteristics of these systems. For example, it makes a big difference whether fishing mortality is preferentially directed to the large biomass year classes--as it is if catch is distributed according to weight--or is based on numbers; or is preferentially directed against smaller fish. In the first case, fishing is stabilizing relative to no effort;* in the second case, it is neutral relative to no fishing; and in the third, it is destabilizing. The phasing of first spawning versus first exploitation can be crucially important in a heavily exploited situation, as is the length of the stock recruitment lag. Finally, the position of the peak in the recruitment curve is a prime determinant of both the dynamic response of the fishery and the optimal level of effort.

We are a little mistrustful of those dynamic models which simply drop the assumption of equilibrium in a simple, two- or three-parameter growth curve, such as the Schaefer quadratic model. There is no doubt that one can obtain valuable qualitative insights from such analyses. But if you really want to manage a fishery, in our opinion you need at a minimum an analysis which explicitly models the population age distribution through time, the species growth curve as a function of age, the stock-recruitment lag, the

*Provided, of course, we remain above the peak in the recruitment curve.

stock-recruitment curve, and the age distribution of the catch relative to the age distribution of the adult stock. Once again, with today's computers there is no computational excuse for not going to such a model.

The simpler dynamic models do have an important role to play in suggesting and pointing toward optimal management strategies. As soon as one realizes one is dealing with a system subject to large amplitude fluctuations under uncertainty, it becomes clear that constant level of effort policies will in general be highly suboptimal and possibly disastrous. One requires feedback between the state of the system and the management policy. Given the instability or near-instability of fisheries such as we have seen in Chapter 5, this sort of adaptive control is probably crucial to the effective management of most fisheries. It also implies a much tougher--by many orders of magnitude--optimization problem. Therefore, simplifications will have to be made.

For example, Palm has shown that, under some very strong assumptions, control theory points to a policy in which fishing effort is a linear function of the deviation from a "target biomass" [Palm, 1975]. Such linear policies are obvious candidates for investigation.* Dynamic programming can handle a somewhat wider class of models with, unfortunately, considerable increase in computational effort. The point is that the strategies suggested by such simpler dynamic models must be thoroughly

*But they must be investigated by models which explicitly describe the lag structures. The possible instabilities inherent in such an "obvious" policy are well known to inventory theorists [Forrester, 1961].

checked out by a model such as FISHDYN1 (or better yet, improvements on such a model) before being considered for implementation. In any event, static, equilibrium analysis appears to us to be completely inappropriate to most fishery management problems, including those currently being faced on the New England continental shelf.

2. Explicit incorporation of key uncertainties.--A second methodological theme of this effort is the thought that, if we have important uncertainties with respect to a fishery, these uncertainties should be incorporated explicitly in our analyses. Once again it is not enough to say, "Let's start Monte Carloing things." What is required is a consistent, coherent method for generating, from the available historical data, probability densities on those variables about which we are uncertain. We have attempted to show by example that Bayesian regression affords us such a method. Once we have derived such densities they can be used in Monte Carlo simulations or, with certain computational limitations, incorporated in dynamic programming or control theory algorithms. We believe that Bayesian reasoning, based on whatever historical data we have, is the way around the perennial objection to aggressive fisheries management: "But we're not sure." Under some generally weak assumptions, the results of such Bayesian analyses are a quantitative reflection of our present state of knowledge, however good or bad that might be. In general, these uncertainties, coupled with simple prudence, should

point to more restrictive policies than if we had complete knowledge about everything.

Having said this, we must again point out a basic flaw in the example of Bayesian reasoning used in this report. This has nothing to do with Bayesian regression in general but rather the specific assumption of the two-parameter Ricker form for the stock-recruitment relationship underlying the data. In this form, the all-important position of the mode cannot be determined independently from the spread-outness of the recruitment curve. The way around this problem is the much more general unnormalized Gamma density. This three-parameter family of recruitment curves has all the good qualities of the Ricker form without its key limitations. Among other things, it contains the Ricker form and constant recruitment as special cases. The single most important improvement we could make to FISHDYN1 is the replacement of the Ricker form with the Gamma. We strongly recommend that all future single-species stock-recruitment work be based on this more general relationship which can truly be said to assume little more than a continuous, unimodal curve which goes to zero at zero and at infinity.

3. The importance of the consumer.--A third theme of our effort is that the fish consumer--or more generally, the fish purchaser--has a stake in effective fisheries management which is of the same magnitude as that of the fisherman. Only if landed price is perfectly elastic can

the fish consumer properly be ignored. Our empirical studies indicate a strong price-landings relationship for all the species we examined except herring. Hence, changes in real consumer income associated with underfishing or overfishing can be as large as changes in fisherman income for most important New England stocks. The authors believe and at least implicitly suggest that the proper objective of public fishery management should be the maximization of present-value real national income (the so-called social surplus), the sum of fisherman and fish consumer income. However, FISHDYN1 itself is neutral on this issue. It can be used to study various policies from the point of view of fisherman income, consumer income, or any combination that strikes the user's fancy.

Moreover, our specific results for yellowtail indicate that one can easily make too much of the fisherman-fish purchaser conflict. The yellowtail results indicate that both the fisherman and fish consumer have a common stake in preventing gross overfishing and gross overfishing. Further, everywhere in the rather narrow range where the fishery is neither being overfished nor underfished, both fisherman and fish consumer income are at near-optimal levels. Hence, both groups have an awful lot in common in seeing that effort is restricted to near-optimal levels. Now this way may not be true for all fisheries, but at least it should be checked out with a model which incorporates the consumer side.

In order to estimate fisherman income or fish consumer income in a situation where landed price is not perfectly elastic, one must incorporate a demand curve (or set of demand curves) within the model. We noted that in so doing, analysts often assume logarithmic or linear relationships which exhibit constant or increasing elasticity with decrease in landings. If one has a fishery in which the demand curve becomes more inelastic as landings decrease--as appears to be the case in at least some of the New England groundfish markets (which turn perfectly elastic at very high levels of landings)--such functional forms can be seriously misleading. The analyst should be aware that when he chooses a functional form for a demand curve, he is also making some very strong assumptions about the elasticity behavior.

6.2 Implications for Georges Bank yellowtail management

When we turn to the practical problem of what to do about the Georges Bank yellowtail fishery, our conclusions will have to be a little more guarded. Under the specific set of assumptions used in the yellowtail production runs, the model strongly argues (a) that the stock cannot sustain a catch of more than 8,000 or 9,000 tons per year; (b) that even with absolutely no foreign effort, present levels of American effort must be cut by a factor of two if we are to obtain anywhere near optimal economic yield from the fishery--from the point of view of both the fisherman and the fish purchaser.

How much credence can we place in these pessimistic results? Where could the model go wrong, and how badly?

The growth curve is reasonably well established and not, we think, a cause for serious debate. The initial (1976) population distribution used in these runs is based on ICNAF estimates for the 1975 standing stock. As such, in a declining industry, it is inherently optimistic. More recently, the New England Regional Council has estimated the 1976 population density [1977, p. 113]. Table 6.2.1 compares these estimates with the ones used in the yellowtail runs. The Regional Council estimates, which are based on more recent data, are roughly 20% lower than the initial population we assumed. Further, we assumed that the 1976 juvenile stock was such that initial (1977) recruitment would be fifty-one million fish. The Regional Council, based on up-to-date juvenile surveys, used forty-two million fish. In short, our initial population estimates may well be off, but if so, they are almost certainly off on the high side.

The natural mortality rate we used, .2, could be a little high. One author has suggested it could be as low as .1 [Lux and Nichy, 1969]. In order to determine the importance of the natural mortality rate to our overall results, a series of runs was made in which natural mortality was set to .1 for all age classes. Otherwise, the assumptions were exactly the same as in Section 5.3.2. Recruitment Mode B, deterministic Ricker based on the 1963-1975 data, was used. The results indicated that the optimal level of effort from the point

TABLE 6.2.1
COMPARISON OF POPULATION DISTRIBUTION ESTIMATES,
YELLOWTAIL EAST OF 69°W

Age	ICNAF Estimates ^a for 1975 (Used in Chapter 5 Runs) (Thousands of Fish)	New England Council Estimates ^b for 1976 (Thousands of Fish)
2	48,900	42,000
3	29,900	21,979
4	11,600	7,689
5	5,500	4,487
6	2,000	1,527
7	800	392
8	200	277
9	100	
10		
Total	99,000	78,341

^aICNAF Secretariat [1976].

^bNew England Regional Council [1977].

of view of social surplus was about 4,500 days. The maximum sustainable yield is just under 10,000 tons. And a fishing effort of 5,400 days is sufficient to send the stock into steep decline, even with a 10,000 ton quota. In short, under this almost certainly optimistic assumption about natural mortality, the fishery can support three or four more "standard vessels" than it could under the assumptions of Chapter 5. Hence, the assumption about natural mortality is not all that important to the overall policy implications of our results, although the 10,000 ton quota is almost low enough to prevent the fishery from going into further decline under this optimistic assumption about natural mortality.

The catch parameters were deliberately chosen to be on the conservative side. Under our assumptions, the upper bound on an individual sixty-five-foot dragger's catch is about 330 tons per year, or about two tons per day fished. These vessels have regularly averaged more than this in past years. Therefore, it appears unlikely that we are overstating the capabilities of these vessels, especially since a significant and growing proportion of the fleet consists of stern trawlers with inherently greater fishing power. The assumption that catch is based on year class weight, while it may be untrue, is an optimistic one. If we had assumed catch based on year class numbers, the overall results would have been more pessimistic. A catch preferentially directed at the small fish would have generated still sadder results. In short, on the catch side,

we have been, if anything, overly optimistic. Most other assumptions possible would point to still lower levels of effort.

This leaves our old nemesis, recruitment. It is possible that our recruitment assumptions, although they're based on twelve years of data, are pessimistic. For one thing, the "data" is really the result of a Virtual Population Analysis (VPA) and not a direct observation. Hence, these figures are subject to all the errors possible in VPA. In fact, as mentioned on page 92, recent evidence indicates that the sampling process used in developing the 1963-1975 figures was probably biased against small fish. More young fish were being caught than these earlier samples indicated. Such a bias would understate recruitment (as well as fishing mortality). Secondly, the Ricker form may be overrestrictive, as we have argued earlier. Third, we may just have been immensely unlucky over the 1963-1975 period. Therefore, it is worth testing the sensitivity of our results to other more optimistic recruitment hypotheses. To do this, we ran three series of runs in which recruitment, 1976-2000, was assumed to be fixed at seventy million age 2 fish, 80 million age 2 fish, and ninety million age 2 fish respectively. The overall results are summarized in Table 6.2.2. In these runs, all other assumptions were exactly the same as in Section 5.3.1. For assumed levels of recruitment of eighty million fish or less, a 10,000 ton quota by itself is unable to prevent the fishery from sliding onto the wrong side of the Ricker curve and going into steep decline. According to the model, in order for the 10,000 ton quota to be truly

TABLE 6.2.1
OVERALL RESULTS FOR VARIATION IN FIXED RECRUITMENT ASSUMPTION. NOTE THAT UNDER FISHDYN1'S ASSUMPTIONS A 10,000 TON QUOTA ACTUALLY LIMITS CATCH TO ABOUT 10,700 TONS PER YEAR.

1976-2000 Level of Recruitment (Million Age 2 Fish)	Maximum Sustainable Yield Under Constant Effort ^a (Metric Tons/Year)	Social Surplus Optimum Level of Effort (Standard Days Fished)	Level of Effort Sufficient to Send Fishery Into Steep Decline With 10,000 Ton Quota	Level of Effort Sufficient to Send Fishery Into Steep Decline Without Quota
51	7,600	3,600	4,050	4,050
70	9,500	4,250	4,800	4,800
80	10,300	5,250	6,000	5,700
90	11,300	5,400	b	6,100

^aBy laying off the fishery completely for a while, it may be possible to generate a stock which will sustain somewhat higher levels of effort. Such non-constant effort policies were not thoroughly investigated but a few examples of this behavior were observed for the higher levels of recruitment.

^bFor constant recruitment of 90 million fish, a 10,000 ton quota will result in biomass growth for all possible levels of effort.

effective in preserving the stock, recruitment must average more than eighty million fish per year for the next twenty-five years. Since the highest recruitment estimated by Parrack is sixty-seven million fish, in order to defend the 10,000 ton quota one must assume an average level of recruitment which is higher than Parrack's highest. In summary, while large-scale uncertainties about recruitment remain, they cannot be used by even the most optimistic observer as an argument against large-scale reductions in present domestic effort, or failing that, a steep reduction in the current quota.

One other possibility remains, and that is that NMFS's present system of counting all trips whose landings are 50% or more yellowtail as being entirely directed against the species, overestimates the amount of effort being directed against yellowtail. This is possible but unlikely. It would imply that fishermen are spending more time looking for other species unsuccessfully than they are for yellowtail unsuccessfully. Since yellowtail are at or near the top of the species list in landed price, this implies in turn that fishermen don't know their business. Otherwise in a fishery in which yellowtail is the dominant species, the NMFS should work pretty well. In a more than two-species fishery in which yellowtail is not strongly dominant, it would understate the level of effort being directed against yellowtail.* Since yellowtail is the dominant species in its principal port of landing, it seems difficult to argue that the NMFS estimate could be too far off.

*For obvious example, consider a three-species fishery in which each trip is evenly devoted against each species with equal results. The NMFS system would end up counting no effort directed against any species.

In summary, then, we can find no strong reason for not giving the model's pessimistic results extremely careful consideration. If they are ignored and prove even approximately correct, we will lose this stock as an economic resource. The loss in fisherman net income, as opposed to the situation under enlightened management, will be about \$5 million per year; the loss in net national income, about \$9 million per year.

The model suggests that a quota in the neighborhood of 7,000 to 8,000 tons will be sufficient to preserve the stock. Now the difference between 8,000 tons and 10,000 tons may appear to be pretty small potatoes in view of all the assumptions and uncertainties which are buried in the analysis. However, if there is one overriding qualitative result in our analyses, it is that the difference between overfishing and underfishing can be quite fine indeed. Examination of Figures 5.2.2, 5.3.9, and 5.4.3 will reveal that the range of levels of effort at which the fishing is anywhere near optimally managed is quite narrow. More importantly, the costs of "slightly" overfishing are extremely large indeed--much larger than the costs of slightly underfishing, especially for the fisherman. In such a situation, a quota difference of 20% or 30% can be of crucial importance. The model claims that setting the quota 25% too high will result in a 250% reduction in catch within five years. Further, in view of all our uncertainties, simple prudence would dictate that if we're going to miss, let it be on the

low side rather than the high. This is especially true in view of our earlier discussion indicating that most of our arguable assumptions are optimistic rather than the reverse.

Of course, as new and presumably better estimates of the uncertain variables become available, they should immediately be submitted to FISHDYN1 and these analyses repeated. The same thing is true with respect to improvements to the model itself. But once again we emphasize that our current uncertainties cannot be used as an argument for delaying firm, effective management. Each decision must be based on whatever information we have at the time of that decision. And right now that information clearly indicates that the current level of effort on the Georges Bank yellowtail should be cut drastically. In a rational world, our present uncertainties coupled with simple procedure would dictate that we overdo this cutback process rather than the opposite, for the model is quite adamant that the costs of overfishing are much higher than the costs of underfishing, especially for the fisherman.

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