VALUE OF INFORMATION IN PACIFIC SALMON (ONCORHYNCHUS SPP.) FISHERY MANAGEMENT: THE SKEENA RIVER TEST FISHERY

by

Gregory John Steer
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Title of Thesis/Project/Extended Essay

VALUE OF INFORMATION IN PACIFIC SALMON (ONCORHYNCHUS SPP.)
FISHERY MANAGEMENT: THE SKEENA RIVER TEST FISHERY

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ABSTRACT

A Monte Carlo simulation model of the commercial gillnet fishery for sockeye salmon (<u>Oncorhynchus</u> <u>nerka</u>) returning to the Skeena River, British Columbia, is used to evaluate the benefits of forecasts of annual returns of sockeye salmon based on test fishery and commercial fishery data. The test fishery is economically efficient; its net annual benefit is between $234,000 and $544,000. In the sensitivity analysis of the results, benefit decreased to equal cost only when the current variance of the pre-season forecast of returns was reduced by 75%. The benefit of test fishery information would be difficult to detect using actual data because the improvement in mean annual catch is small relative to the variability in annual catch. This problem of detectability could lead to termination of fishery management initiatives that are, on average, economically efficient.

In the analysis of the dynamics of the commercial gillnet fleet in Area 4 (Skeena River) from 1966 through 1980, I found that the fleet exhibited an aggregation response to changes in stock abundance and that the catchability coefficient of the gillnet fleet (proportion of the fish stock caught per unit of fishing effort) was dependent on stock abundance and/or fishing effort. This dependence could lead to overharvest of fish stocks at low levels of stock abundance.

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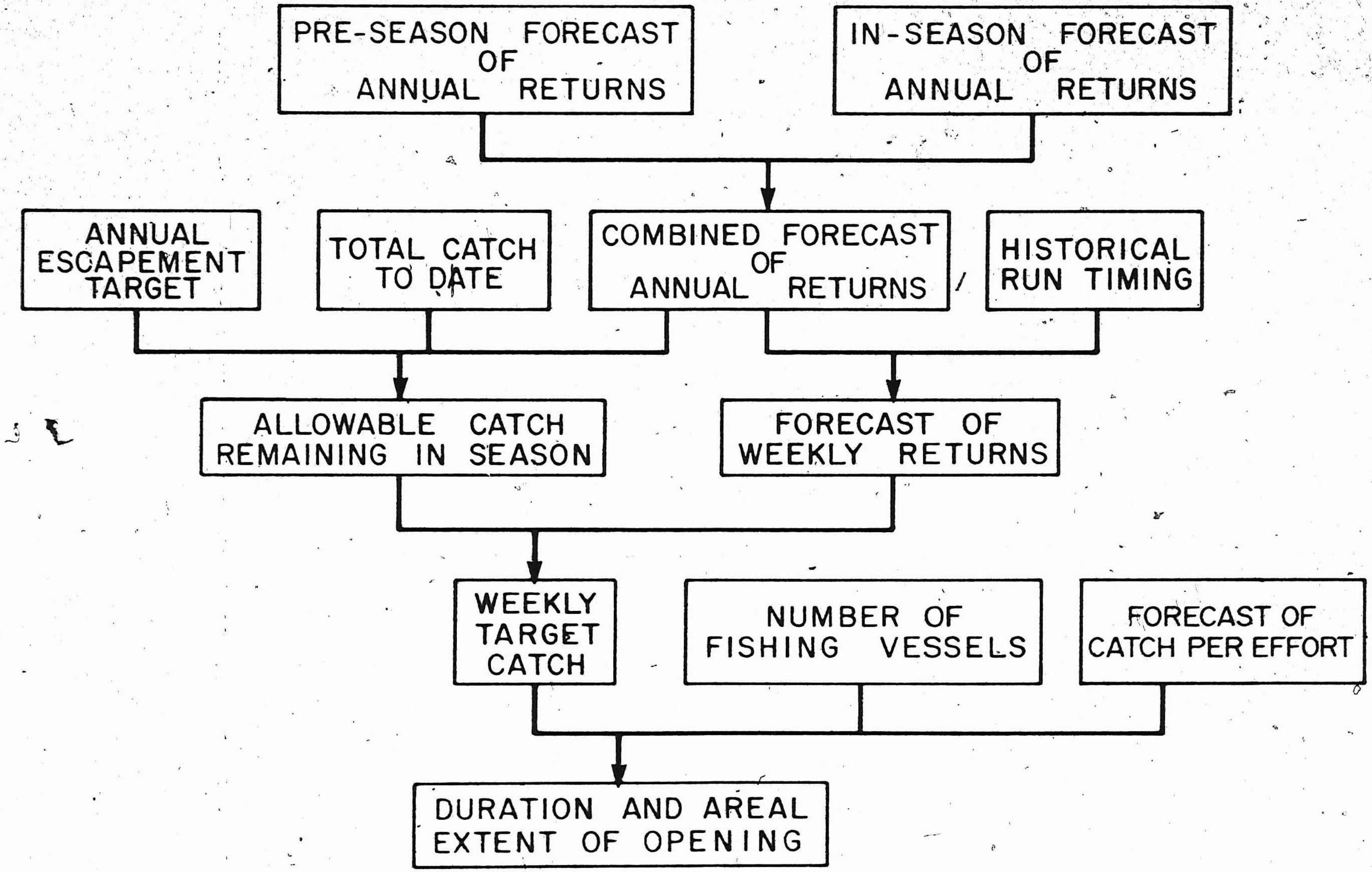
I. General Introduction

Pearse (1982) recommended establishing test fisheries on the coast of British Columbia to improve within-season management and utilization of Pacific salmon (Oncorhynchus spp.) stocks. He recommended test fisheries because decisions on daily openings or closures for commercial fishing are made for most salmon stocks on the basis of pre-season forecasts of return abundance or catch per unit effort (C/f) in the commercial fishery, both of which have inherent problems. Because of large interannual variation in marine survival rates, pre-season forecasts are typically imprecise (Eggers et al. 1983). For the commercial fishery to provide C/f data on which to base an in-season forecast of abundance of returns, the fishery must be open and once closed for conservation reasons, will not reopen in the absence of other in-season forecasts of return abundance. Thus, a large but late-arriving salmon run could go underharvested. Also, the key assumption in using commercial fishery C/f as an index of abundance of returns is that the catchability coefficient (q) is constant. However, this assumption is potentially violated by a number of factors. Catchability may vary due to changes in stock abundance and spatial distribution (Paloheimo and Dickie 1964, Peterman and Steer 1981, Crecco and Savoy 1985, Winters and Wheeler 1985), to changes in fishing power (Gulland 1964, Ledbetter 1983) as fishermen seek to increase q and maximize C/f, or to changes in fishing effort (Rothschild 1977, Ledbetter 1983). The assumption is also explicitly violated by regulations, such as subarea closures or gear restrictions that decrease q, aimed at controlling exploitation rates despite excessive numbers of fishing vessels. The combination of these sources of variation in q reduces the precision of abundance estimates calculated from commercial C/f and thereby reduces the chance that management goals will be met, if management actions are taken on the basis of C/f alone, as detailed below.

An alternative to using commercial C/f as an in-season index of stock abundance is a test fishery (Sprout and Kadowaki 1987, Minard and Meacham 1987). Unlike a commercial fishery, a test fishery takes only a small proportion of the salmon run, so it can operate continuously throughout the run without danger of overharvesting the stock. It usually consists of a series of standardized gillnet samples designed to maximize precision of abundance estimates. These samples are usually taken by a boat not involved in the commercial fishery. They produce a standard C/f that is not confounded by the harvester's objective of revenue maximization or by the fishery manager's objective of controlling the rate of exploitation. This standard C/f is combined with a relationship between abundance and C/f derived from previous years' data to estimate daily or weekly abundance of escapement, if the test fishery occurs upriver of the commercial fishery, or abundance of returns, if it occurs downriver. Estimates of escapement from the test fishery are combined with catch data to produce estimates of return abundance. These estimates of return abundance can then be combined with historical run timing data to produce a forecast of annual abundance of returns (Walters and Buckingham 1975). Given that test fisheries incur a cost, this study addresses the question: Does the additional economic benefit that arises from using test fishery data outweigh the cost of having the test fishery?

Management of Pacific salmon fisheries is a problem of allocating returns to catch or escapement by indirectly controlling a predator / prey system. Imprecise information on either the catch or escapement can lead to allocations which do not meet management objectives and thus reduce benefits. The harvest component is indirectly controlled by regulating the timing and length of weekly fishery openings by gear type and area. Since the fishery manager must set these regulations in advance of the weekly fishery opening, he must estimate the number of vessels that will fish during the opening and also predict their efficiency. During the fishing season, forecasts of annual abundance of returns are derived from both pre-season and in-season forecasts (Figure 1). Pre-season forecasts are made in advance of the fishery and are based on 1) number of spawners in each brood-year, a stock-recruitment function, and age-at-return data, 2) number of emigrating juveniles, a marine survival function, and age-at-return data, or 3) relationships between returns at successive ages (Peterman 1982, Minard and Meacham 1987, Sprout and Kadowaki 1987, Henderson et al. 1987). In-season forecasts are based on cumulative returns to date and

Figure 1. Flow chart of information used in the management of Pacific salmon fisheries.

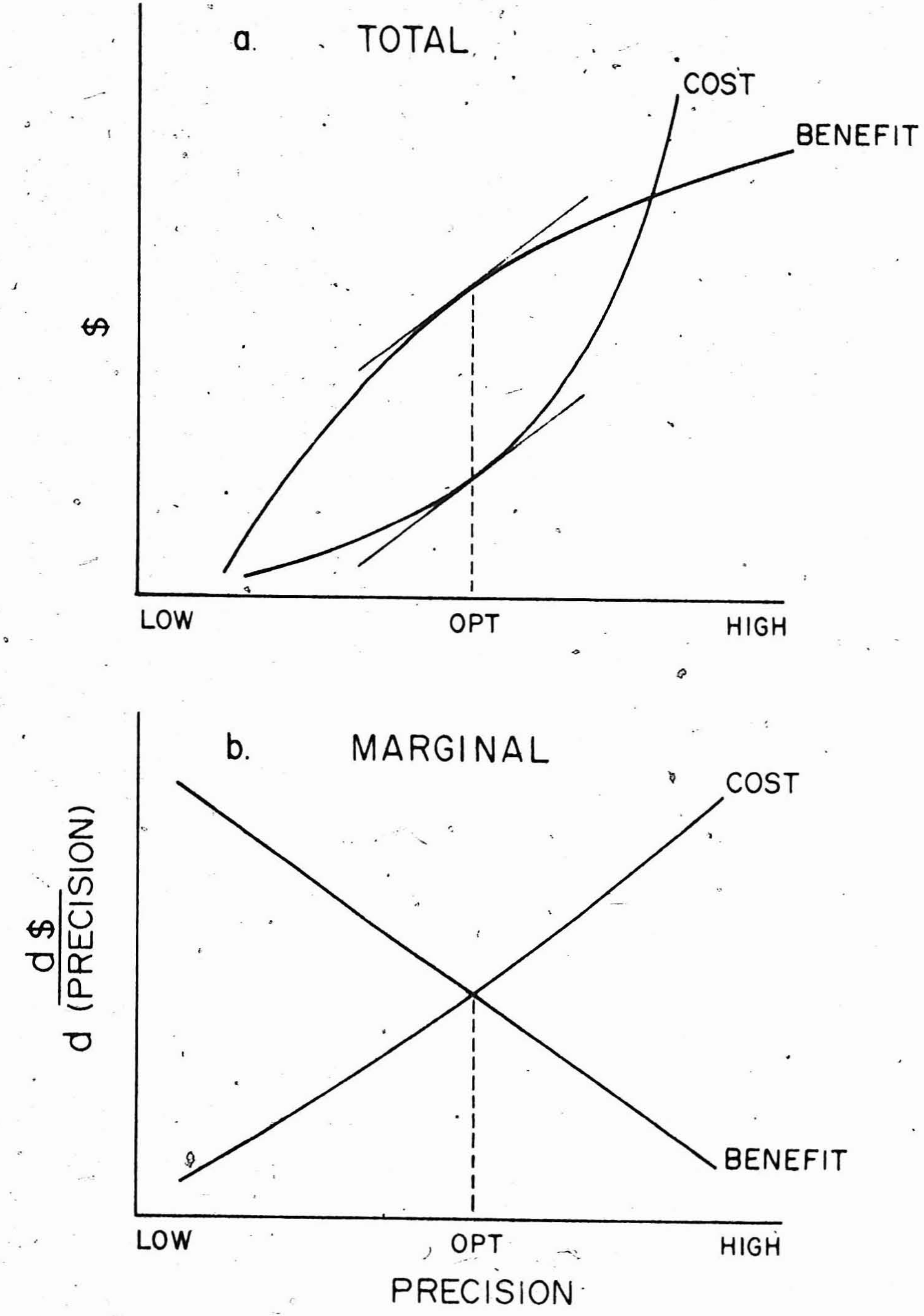

PRE-SEASON FORECAST OF ANNUAL RETURNS
IN-SEASON FORECAST OF ANNUAL RETURNS
ANNUAL ESCAPEMENT TARGET
TOTAL CATCH TO DATE
COMBINED FORECAST OF ANNUAL RETURNS
HISTORICAL RUN TIMING
ALLOWABLE CATCH REMAINING IN SEASON
FORECAST OF WEEKLY RETURNS
WEEKLY TARGET CATCH
NUMBER OF FISHING VESSELS
FORECAST OF CATCH PER EFFORT
DURATION AND AREAL EXTENT OF OPENING

historical run timing data (Walters and Buckingham 1975, Henderson et al. 1987, Minard and Meacham 1987, Sprout and Kadowaki 1987, Steer and Hyatt 1987, Fried and Hilborn 1988). The pre-season and in-season forecasts are combined to produce one forecast which is then applied to an average historical run timing curve to forecast weekly abundance of returns. Pre-season forecasts may not be very precise (Eggers et el. 1983, Henderson et al. 1987, Minard and Meacham 1987, Sprout and Kadowaki 1987) so there is a critical requirement for in-season management information with which to reforecast abundance of returns and then modify fishing plans to meet escapement objectives. Test fishery or commercial fishery C/f provide these in-season estimates of abundance.

The overall objective of the fishery management effort is to manage, conserve, and enhance the anadromous fish stocks for the greatest possible benefit from the renewable fishery resource (Anon. 1984). This involves allocating returns to catch, taken in the current year's fishery, and to escapement, which results in future catches. Catch is allocated among gear types, user groups, and across the sub-stocks that comprise the run. Goals are expressed as target escapements or exploitation rates, and imperfect information about exploitation rate and abundance of returns results in deviations from these goals. Since the catch is a large proportion of annual returns, small percentage deviations from annual catch objectives produce large deviations from annual escapement targets. Also, larger runs generally lead to larger deviations from escapement targets (Bocking and Peterman 1988).

More and better information will improve the chance of meeting these objectives by reducing the magnitude of deviations from escapement and allocation targets. However, the fishery manager has limited resources to use for acquisition of information and is faced with an array of information types from which to choose, each with various levels of precision and cost. The manager controls the precision of the information by altering the experimental design or the level of sampling effort but is interested in how this change in cost relates to decreased deviations from objectives. Benefit-cost analysis provides a quantitative framework that can be used for the evaluation of these alternatives. One objective that can be used in a benefit-cost analysis is to maximize net revenue from the fishery (Figure 2). The optimal level of precision of forecasts of abundance of salmon returns is the level where the marginal cost of acquisition of information equals the marginal benefit of that information to the fishery. For example, the optimal level of sampling effort is the level where the additional benefit due to the improvement in precision associated with taking one more sample is just less than the cost of taking that additional sample. Costs associated with each alternative type of information and level of sampling effort are relatively easy to measure but benefits to the fishery are more difficult to assess due to the complex interaction of management, harvesters, and prey.

Figure 2. Theoretical relationships between (a) total cost, total benefit, and precision of in-season forecast of return abundance, and (b) marginal cost, marginal benefit, and precision of in-season forecast of return abundance. The optimal level of precision (OPT) corresponds to the level where marginal cost equals marginal benefit (b), which maximizes the difference between total benefit and total cost (a).


a.
TOTAL
COST
BENEFIT
$
LOW
OPT
HIGH
b.
MARGINAL
COST
d $ / d (PRECISION)
BENEFIT
LOW
OPT
HIGH
PRECISION

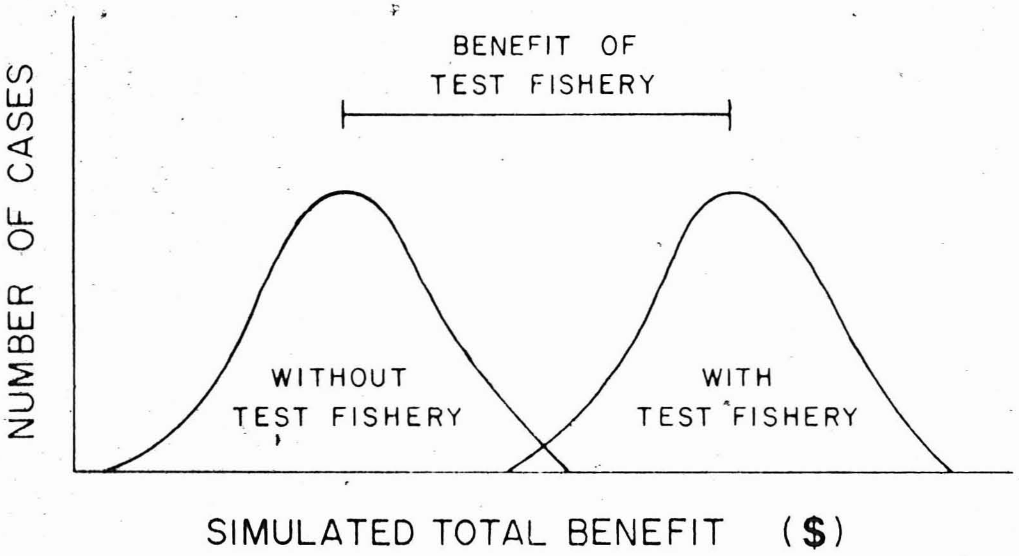
Several authors have studied the salmon fishery management problem but they have not quantified the benefits and costs of improved in-season return forecasts from a test fishery. Paulik and Greenough (1966) conceptualized the salmon management problem but did not apply their analysis to a specific fishery. Walters and Buckingham (1975) formulated a stochastic simulation model of the Skeena River sockeye salmon (O. nerka) and pink salmon (O. gorbuscha) fishery and found that although perfect pre-season forecasts of return abundance reduced the variance in annual exploitation rates, perfect forecasting did not eliminate it. Mathews (1971) presented a simulation analysis of the Bristol Bay salmon fishery and quantified the benefits to the processing sector associated with two levels of precision in pre-season return forecasts. He found that although benefits to the fish processors increased with an improvement in the precision of pre-season forecasts from a current error level of +/- 50% to an error level of +/- 10%, he contended that the increased benefit was exceeded by the increased cost of reducing forecasting error to that level. Neither Walters and Buckingham (1975) nor Mathews (1971) determined the benefits and costs of improved in-season forecasts of returns. Lord (1976) presented an analytic model of in-season salmon management that calculated average deviations from maximum sustained yield associated with an optimal schedule of fishery openings. He simulated the management of the Wood River sockeye salmon fishery using data from Mathews and found that more precise in-season estimates of return abundance decreased the expected loss in catch, i.e. the average reduction in catch from maximum sustainable yield. For analytic tractability, his model greatly simplified the fishery management problem. For example, he reports that there can be considerable between-year variation in return timing, which affects the precision of in-season forecasts of return abundance, but his model assumed that run timing was constant and known. Also, the only management action in his model was to open or close the fishery each week. In reality, fishery managers regulate the timing and length of fishery openings to meet weekly objectives for catch or exploitation rate. He noted that capturing the fishery management problem with greater realism would likely require the use of Monte Carlo simulation.

The purpose of this work is to use Monte Carlo simulation to determine the benefits and costs associated with a test fishery, incorporating interannual variability in timing of salmon runs and variable duration of fishery openings. Stochastic simulation can model the complex relationship between fishery performance and improved forecasts of abundance of returns. It provides an estimate of the mean change in a variable resulting from a change in management information and an estimate of the variance of the mean change. Both are critical for evaluating the detectability of the expected result, i.e. determining the sample size required to detect a change of the expected magnitude given the inherent level of masking variation in the observations. The stochastic model simulates the weekly behaviour of a commercial gillnet fishery for sockeye salmon (O. nerka) and consists of four components: 1) sockeye salmon population dynamics, 2) fishing fleet dynamics, 3) fishery management, and 4) economic evaluation. The sockeye salmon population submodel consists of a stock-recruitment function, age-at-return data, and in-season timing data to calculate weekly returns to the fishery. The fleet submodel simulates the numerical and functional responses of a gillnet fleet to weekly changes in sockeye salmon abundance. The fishery management submodel calculates the number of days of fishing required to achieve its escapement target, given the fleet size and a forecast of return abundance. To calculate the additional benefit potentially derivable from having a test fishery, management is simulated in different scenarios with and without escapement information from the test fishery. The economic submodel calculates benefits and costs.

Both the mean value ($) of the annual catch and the mean net present discounted value of the annual catch, calculated from 100 simulations of 50 years duration, are used as the criteria for the benefit to the fishery of improved in-season return forecasts from a test fishery. The benefit of the test fishery is calculated by subtracting the value of the catch at the level of precision of in-season forecasts corresponding to the next best alternative from that at the level of precision associated with the test fishery (Figure 3). The next best alternative is either management based on pre-season forecasts or management based on commercial fishery catch per unit effort, whichever produces greatest catch benefit. Net value of the annual catch is the landed wholesale value less costs of harvest. The

Figure 3. Theoretical frequency distribution of total benefit to the fishery with and without test fishery information. Benefit due to test fishery is difference between mean values.

Figure 3. Theoretical frequency distribution of total benefit to the fishery with and without test fishery information. Benefit due to test fishery is difference between mean values.


BENEFIT OF
TEST FISHERY
NUMBER OF CASES
WITHOUT
TEST FISHERY
WITH
TEST FISHERY
SIMULATED TOTAL BENEFIT ($)

sensitivity of these estimates of benefits and costs to uncertainty in parameter estimates and model structure is determined implicitly by the stochastic inputs (Fedra 1980) and explicitly by altering the form of the model's functional relationships between variables.

This study consists of two sections. The first section focuses on identifying the submodel for the dynamics of the gillnet fleet in the fishing area chosen for this study, Pacific Fishery Management Area 4. This fleet harvests sockeye salmon bound for the Skeena River, British Columbia. In this section, I analyze the numerical and functional responses of the commercial gillnet fishery to changes in stock abundance. The second section adds the fleet dynamics submodel to the stock dynamics and fishery management submodels. This section also includes an analysis of sockeye salmon recruitment, age at return, and return timing, which constitute the stock dynamics submodel. The final part of the second section describes the complete model, and its use in addressing the question of the economic benefit of a test fishery.

II. Catchability Coefficients of the Gillnet and Test Fisheries for Sockeye Salmon (Oncorhynchus nerka) in Area 4, Skeena River.

Introduction

Two fundamental problems for managers of Pacific salmon (Oncorhynchus spp.) fisheries are (1) What is the annual abundance of fish that are subject to harvest this year? and (2) How long should the fishery be open to harvest the desired catch? Salmon fisheries are classified as "gauntlet" fisheries (Paulik and Greenough 1966), where the fishing gear intercepts salmon passing through the fishing area en route to the spawning grounds. Fish that are not caught "escape" the fishery. The manager requires a forecast of annual abundance of returns (N_y) to the fishing area in order to calculate the annual catch (C_y) to be harvested, i.e. the excess of abundance over the annual escapement objective (E_y):

$$C_y = N_y - E_y \tag{1}$$

The annual catch objective is composed of weekly catches which the fishery manager indirectly allows by regulating the duration and starting date of weekly commercial fishery openings, based on estimates of vessel numbers and stock abundance.

The solutions to both of these problems require precise estimation of the components of the catch equation. Catch (C) is related to stock abundance (N), nominal fishing effort such as boat-days (f), and the catchability coefficient (q) as follows (Ricker 1975):

(2) $C = qfN$

Annual stock abundance may be estimated during the fishing season from historical patterns of run timing and data on weekly stock abundance.[1] Weekly stock abundance may be estimated using catch per effort data from (1) the commercial fishery, or (2) a test fishery which uses standardized gear and procedures to produce standardized data. The desired duration of the next commercial fishery can then be estimated from the weekly catch objective, the number of fishing vessels, their expected catchability coefficient, and the predicted weekly abundance of the stock. The catchability coefficient is the proportion of the stock caught per unit effort, $q=(C/N)/f$.

Knowledge of the dynamics of the salmon gillnet fishing fleet is important to fishery managers in order to increase the likelihood of taking the correct weekly catch and meeting annual escapement goals. In this chapter, I test several hypotheses about factors that affect q in a test fishery and affect both q and f in a commercial gillnet fishery. These fisheries harvest sockeye salmon (<u>Oncorhynchus nerka</u>) in Pacific Fishery Management Area 4, located on the north coast of British Columbia (Figure 4). This area has the second largest mean

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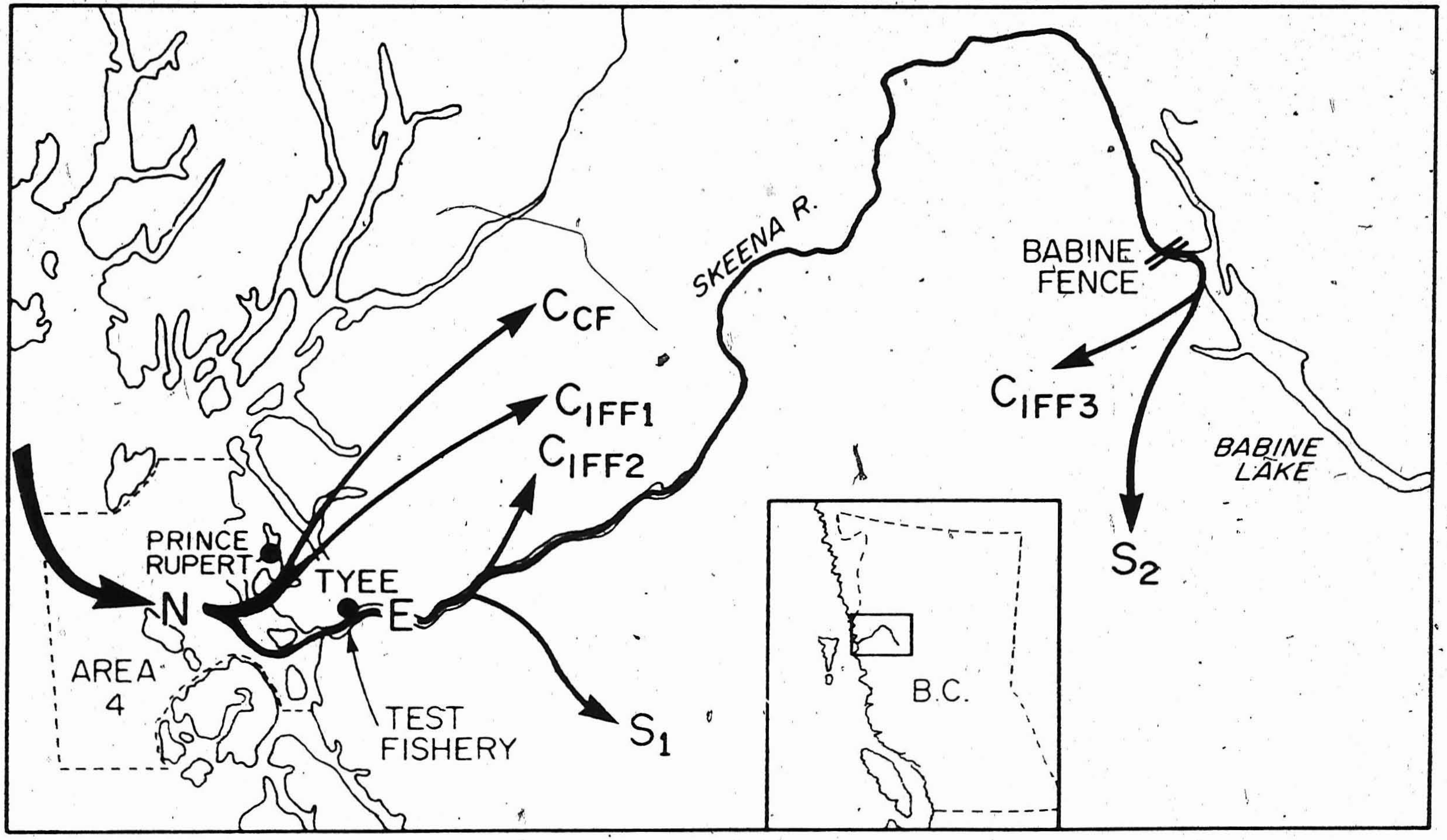
[1] See In-season Forecasts of Annual Abundance of Returns in the next chapter.

Figure 4. Pacific Salmon Fishery Management Area 4 and the Skeena River. Sockeye returns (N) are harvested in Area 4 by a commercial gillnet and seine fishery (C_{CF}) and by three Indian food fisheries (C_{IFF1}, C_{IFF2}, C_{IFF3}), in Area 4 and along the sockeye migration route. Sockeye that escape Area 4 (E) are enumerated by a test fishery at Tyee. Catch per effort data from this fishery is used with catch data to forecast abundance of returns. Spawning (S_1, S_2) occurs below and above the enumeration fence at the outlet of Babine Lake. Abundance of spawners above the fence (S_2) is much greater than that below the fence (S_1).


C_{CF}
C_{IFF1}
C_{IFF2}
C_{IFF3}
SKEENA R.
BABINE FENCE
BABINE LAKE
PRINCE RUPERT
TYEE
N
E
AREA 4
TEST FISHERY
S_1
S_2
B.C.

catch of sockeye on the British Columbia coast and an upstream test fishery has operated there since 1955 for in-season estimation of escapement abundance. These data provided the basis for an empirical analysis of the components of the catch equation (2). In the next chapter, I use these relationships in a computer simulation to assess the value of test fishery information in the management of salmon fisheries.

Below, I review evidence about sources of variation in catchability and effort from other fisheries. This review shows that catchability has been related to stock abundance and fishing effort and that investment in technology may increase catchability over time (Figure 5). Environmental and biological factors, such as water clarity and fish behaviour, may also affect q. Fishing effort has been found to respond to catch and catch per unit effort.

Effect of Abundance of Fish on q

The catchability coefficient may vary with stock abundance. Paloheimo and Dickie (1964) used a theoretical model to predict that non-random searching by fishermen for schools of fish would result in density-dependent q unless the within-school density of fish changed in proportion to the overall density. Peterman and Steer (1981) fitted a power model[1]

$$(3) \qquad C/f = a_3 * N^{b3+1}$$

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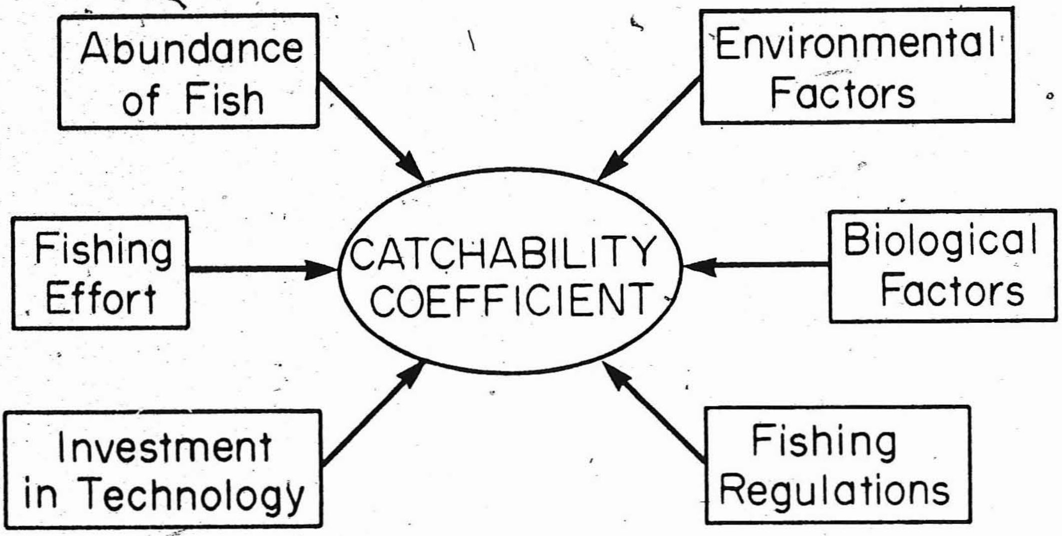
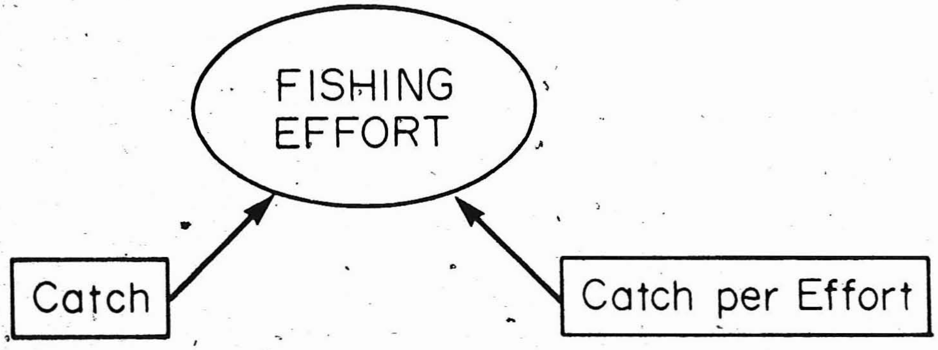
[1] Throughout the rest of this paper, parameters are subscripted with the equation number in which they first appear.

Figure 5. Sources of variation in catchability and fishing effort that have been documented.


Abundance of Fish
Environmental Factors
Fishing Effort
CATCHABILITY COEFFICIENT
Biological Factors
Investment in Technology
Fishing Regulations


FISHING EFFORT
Catch
Catch per Effort

where $q = a_3 * N^{b3}$, and found that q in a sport fishery for chinook salmon (O. tsawytscha) in the Willamette River, Oregon was dependent on stock abundance, i.e. the exponent (b_3+1) was significantly less than 1. Other authors have also found evidence for density-dependent q in other species; see Peterman and Steer (1981) for a review. More recently, Winters and Wheeler (1985) argued that the density-dependent q in a commercial purse-seine fishery for herring (Clupea harengus harengus) in Fortune Bay, Newfoundland resulted from a positive nonlinear relationship between area occupied by fish schools and stock abundance, and a negative nonlinear relationship between q and spatial distribution of the stock. Crecco and Savoy (1985) found that the catchability coefficient of a commercial gillnet fishery for American shad (Alosa sapidissima) in the Connecticut River was inversely related to the abundance of female escapement and attributed this to nonrandom exploitation of patches of female shad.

I tested for density-dependent q in the commercial gillnet fishery for sockeye salmon returning to the Skeena River. Walters and Buckingham (1975) fitted data on weekly harvest rate and gillnet effort in 1971-73 for the same system but did not test their hypothesized relationship for statistical significance, i.e. $P(b_3+1)=1$ in equation 3. However, they comment that a given level of effort produced a greater harvest rate at low stock sizes than at high stock sizes, suggesting density-dependent q. Brannian (1982) calculated daily q in a gillnet fishery for sockeye salmon in Togiak Bay, Alaska but also did not test for density dependence.

Effect of Fishing Effort on q

I also tested whether q depended on nominal fishing effort (e.g. boat-days), as might result from facilitative or competitive interactions among fishing vessels or from changes in fleet composition. Harvest rate, defined here as C/N, may increase disproportionately with increasing nominal effort if fishing vessels cooperate in searching for prey or may decrease disproportionately with increasing nominal effort if they interfere with one another, e.g. in limited areas for fishing (Rothschild 1977). Average catchability will also decrease with increases in nominal effort if the additional units of effort are less proficient at catching fish. Hilborn (1985a) argues that there are two successful fishing strategies employed by fishermen to maximize catch: 1) area specialization, where q is maximized for one area, and 2) movement specialization, where a fishing area is selected to maximize the abundance of fish available to be caught, N. Thus, the relatively high average q of the area specialists at low effort levels would be diluted by the attraction of the relatively less proficient movement specialists at high effort levels.

These theoretical effects of changes in effort on q have been documented or implied by several studies. The exchange of information among fishermen on fish distribution is one form of cooperation that decreases search time and it may be deliberate or inadvertent, in the case where information transmitted via radio is intercepted (Ledbetter 1983). The effects of competition for limited fishing locations were documented by Ledbetter (1983) who found that the length of queues of seine vessels for salmon fishing locations in Johnstone Strait, British Columbia increased with catch per set at those locations and resulted in strong interference competition. Catchability may decrease disproportionately with increasing effort if the additional units of effort are less effective and change the composition of the fleet. Walters and Buckingham (1975) fitted an asymptotic equation to gillnet harvest rate and effort data from the Skeena River in 1971-73 but again did not test the hypothesis that q decreased with increasing effort. Brannian (1982) reported a decrease in q with increasing gillnet effort but her hypothesis tests were confounded by the mutual dependence of q and f.

Effect of Time on q

Catchability of the gillnet fleet may change over the years due to the net effect of changes in fishery regulations that reduce q over time and changes in technology and fleet composition that increase q over time. For example, q can be reduced through regulation by closing areas to fishing where fish are concentrated (Hyatt and Steer 1987). Pearse and Wilen (1979) found that Canada's Pacific salmon fleet rationalization program limited the number of fishing vessels but did not prevent investment in fishing technology that could improve q. The seine drum, bow thruster, and running line increased fishing power of the B.C. purse seine fleet in the 1960s and 1970s by reducing the amount of time required to make a set (Ledbetter 1983). In the British Columbia gillnet fleet between 1965 and 1977, average engine horsepower increased by 47%, average vessel length increased by 6%, and average net tonnage increased by 24% (Fraser 1979). I tested for time trends in the q of the gillnet fleet by using the test fishery as a control for other environmental and biological factors, such as water clarity and fish behaviour, that may affect q. The test fishery is a control in the sense that it has used rigorously standardized procedures and gear to fish for Skeena sockeye since 1966.

Effect of Abundance of Fish on Fishing Effort

If fishermen behave as predators, I would expect an aggregation response to changes in true abundance of prey, i.e. more boats would be attracted to fishing areas with high stock abundance. Fishing effort has been related to indices of abundance such as catch (Botsford et al. 1983, Hyatt and Steer 1987) and catch per unit effort (Walters and Buckingham 1975, Hilborn and Ledbetter 1979, Peterman et al. 1979, Argue et al. 1983, Millington 1984). For example, Hyatt and Steer (1987) found a correlation between the maximum number of gillnet vessels fishing and annual returns of sockeye in Barkley Sound, British Columbia. I explicitly tested for a within-season aggregation response by the Area 4 gillnet fleet to changes in abundance of sockeye salmon because weekly fleet size affects the duration of fishery required to take the weekly catch objective.

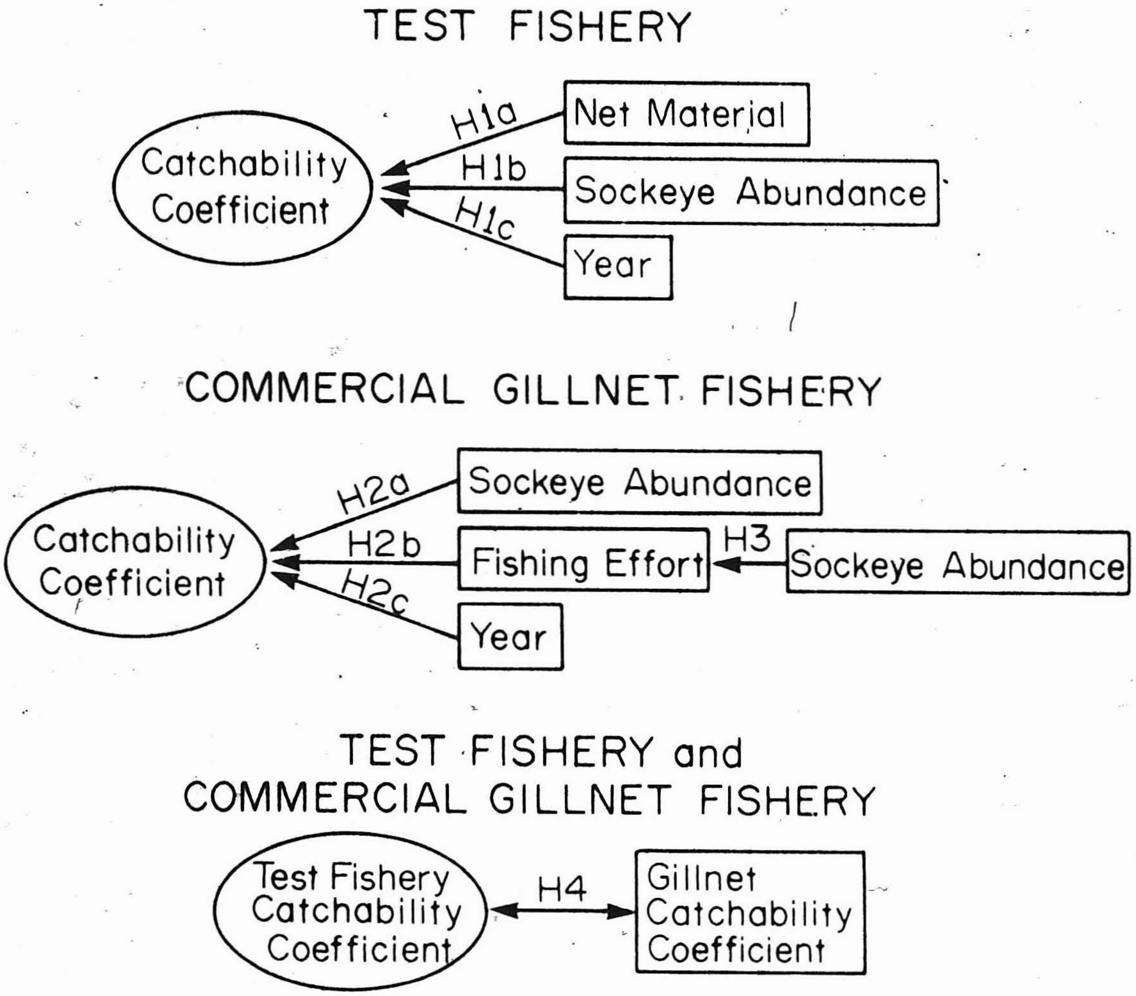
General Methods

Analysis of the components of the catch equation (Equation 2) requires estimates of catch, nominal fishing effort, and stock abundance on an appropriate time scale. The basic unit of time for my in-season calculations of fishing effort and stock abundance was one week. A time step of one week reduces data requirements from those of a daily time step and is consistent with management objectives made on a weekly basis. Models requiring data on a daily basis are often forced to calculate daily estimates from weekly data. For example, Schnute and Sibert (1983) distributed data collected on a weekly basis into daily estimates using linear interpolation. Since vessels may accumulate catch during multi-day openings, it is difficult to determine actual dates of catch from data on landings. Also, Pacific salmon management objectives in British Columbia are set on a weekly basis (e.g. weekly target catch or harvest rate) to meet annual objectives.

Test Fishery Hypotheses

Analysis on a weekly basis requires estimates of weekly escapement. Therefore, I first analyzed sources of variation in test fishery q (Figure 6) because I used weekly C/f in the test fishery to calculate these estimates of escapement. In this calculation, *test fishery catch per effort is implicitly assumed to be density independent. This assumption is reasonable*

Figure 6. Sources of variation in test fishery q and in commercial gillnet fishery q and f. The number of the working hypothesis is indicated on each arrow.



TEST FISHERY

COMMERCIAL GILLNET FISHERY

TEST FISHERY and COMMERCIAL GILLNET FISHERY because 1) set length is short to reduce the potential for net saturation, 2) there is no searching for fish schools, and 3) there is no competition with other fishing vessels. Since I do not have independent estimates of weekly abundance at the test fishery site, I used annual data to test the following working hypotheses on the effects on test fishery q of:

H1a: net material
H1b: sockeye abundance
H1c: year

Commercial Fishery Hypotheses

I then combined the estimates of weekly escapement with weekly catch data to calculate weekly abundance of sockeye in Area 4 which I used to test working hypotheses concerning sources of variation in weekly q and f in the commercial gillnet fishery (Figure 6). I used weekly data to test the effects on commercial gillnet q of:

H2a: sockeye abundance
H2b: fishing effort

and annual data to test the effect of:

H2c: year

I used annual data to test for time trends in q because the mechanisms of change, investment and gear regulation, operate on an annual time scale and because the control, test fishery q, is only available on an annual basis. I used weekly data to test the effect on weekly fishing effort of:

H3: sockeye abundance

Finally, I tested for a correlation between annual q in the test fishery and annual q in the commercial gillnet fishery:

H4: Correlation between q_{TF} and q_{GN}

where q_{TF} is test fishery q and q_{GN} is commercial gillnet fishery q.

Data Sources

Sockeye returning to Area 4 are primarily harvested by a commercial gillnet and seine fishery in Area 4 (Figure 4). Escapement from Area 4 is enumerated by a test fishery at Tyee and spawners entering Babine Lake are counted at a fence at the lake outlet. Indian food fisheries for salmon occur in three locations: (1) downstream from the test fishery site, (2) between the test fishery and the Babine River counting fence, and (3) above the Babine fence.

Commercial Fishery

Weekly catch data from sales slips of salmon landings by the Area 4 commercial fishery and daily estimates of gillnet effort from 1966 through 1980 were supplied by S. Benoit (Department of Fisheries and Oceans (DFO), Vancouver, B.C., personal communication). Daily estimates of effort were summed to yield estimates of weekly gillnet effort. Effort on the first day of an opening was estimated by DFO management biologists flying over Area 4 in a chartered aircraft who enumerated all fishing vessels. Effort on subsequent days was calculated by adjusting this figure for vessel immigration and emigration as estimated by Fisheries Officers on patrol vessels.

For weekly functional and numerical response analyses, I used data from continuous openings whose first day was at least one day removed from the previous opening's closure (Table 1). The objective of this criterion was to minimize misallocation of catch between weeks. Openings associated with strikes and those for which I could not positively assign catch to a week were also omitted from the weekly analyses.

River Fisheries and Escapement

In the Skeena River, Indian food fisheries for salmon occur at three locations: (1) downstream from the test fishery site, (2) between the test fishery and the Babine River counting fence, and (3) above the Babine fence. Estimates of annual catches in these three fisheries and of annual abundance of sockeye spawners in Area 4 for return years 1966 through 1980 were provided by C. West (DFO, Vancouver, B.C., personal communication). The three Indian food fisheries harvested about 10% of the Area 4 escapement so measurement errors inherent in those data should not seriously affect the analysis. The presence of the Babine River counting fence, which allows complete enumeration of escapement, throughout the study period

Table 1. Data used in annual and weekly analyses of the Area 4 gillnet and test fisheries for sockeye, 1966-80. Start and finish dates are indicated for the test fishery. First and last commercial fishery weeks indicate period for which corresponding escapement estimates from the test fishery are available. Only fishery openings which were open continuously and opened at least 1 day removed from the previous closure were used. Commercial fishery openings are designated as month and week number, e.g. 7-1 is the first week in July.

Year	Test Fishery Start	Test Fishery Finish	Com Fish 1st	Com Fish Last	Commercial fisheries used in this analysis
1966	14 Jun	28 Aug	6-4	8-4	7-1, 7-2, 7-5, 8-3, 8-4
1967	14 Jun	29 Aug	6-4	8-4	7-1, 7-2, 8-1, 8-2, 8-4
1968	15 Jun	25 Aug	6-3	8-4	7-1, 7-2, 8-1, 8-3
1969	13 Jun	30 Aug	6-3	8-3	6-4, 7-1, 7-2, 7-3, 7-4, 7-5
1970	14 Jun	26 Aug	6-3	8-3	6-4, 7-1, 7-2
1971	14 Jun	27 Aug	6-3	8-3	7-1, 7-3, 7-5, 8-1, 8-2, 8-3
1972	15 Jun	25 Aug	6-4	8-3	7-2, 7-3, 8-2, 8-3
1973	14 Jun	28 Aug	6-3	8-3	6-4, 8-1, 8-2
1974	17 Jun	28 Aug	6-3	8-3	7-1, 7-2, 7-5, 8-1, 8-3
1975	16 Jun	26 Aug	6-3	8-3	7-1, 7-2
1976	13 Jun	27 Aug	6-3	8-3	
1977	13 Jun	26 Aug	6-3	8-3	7-2, 7-3, 8-1, 8-2, 8-3
1978	13 Jun	27 Aug	6-4	8-4	7-2, 7-3, 7-4, 7-5, 8-2, 8-3, 8-4
1979	11 Jun	26 Aug	6-2	8-3	7-2, 7-3, 7-4, 7-5, 8-1, 8-2
1980	12 Jun	27 Aug	6-3	8-3	7-3, 7-4, 7-5

Data Omissions :

1972 - Week 6-4 : vessel count but no reported catch
1973 - Weeks 7-1 & 7-2 : strike
1975 - Weeks 7-3, 7-5, 8-1, 8-2 & 8-3 : strike
1976 - Whole year : Difficulty in assigning catch to opening

reduced the problem of measurement error normally associated with escapement data (e.g. Walters and Ludwig 1981) because sockeye migrating through the Babine River comprised 96% of the total Area 4 spawners.

Test Fishery

Catch and effort data for the Skeena River test fishery were supplied by R. Kadowaki (DFO, Prince Rupert, B.C., personal communication). The test fishery operates from mid-June, the start of the sockeye run, through late August (Table 1), well after the end of the sockeye run, using procedures and gear that have been rigorously standardized since 1966 except for a change in net material in 1969 (Kadowaki, unpublished MS). The test fishery uses an undyed fibrous nylon gillnet, 200 fathoms (366 m) long by 20 feet (6 m) deep, consisting of ten equal length panels of mesh sizes 3.5 in (8.9 cm) to 8 in (20.3 cm) to minimize size selection, and hung in a ratio of webbing to finished length of 2.5:1, to reduce net efficiency and minimize saturation. In 1969, the net material changed from twisted 7-ply twine to a limper, untwisted material. Subsequent analysis showed that this change had no effect on catchability.[1] Two or three one-hour sets per day are made during daylight on the high and low water slack tides. During each set, the net drifts in a channel, 2 to 5 km long by 0.8 km wide, running parallel to the northern shore of the Skeena River near Tyee. Sets made at low tide catch approximately twice as many fish as those at high

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[1] See below for Effect of Change in Net Material on q.

tide. The low tide set covers twice the distance of the high tide set, samples a larger proportion of the cross-sectional area of the river and is made closer to the north shore, a migration route preferred by sockeye. The test fishery has been contracted to the same skipper and vessel since 1966, an important factor that minimizes year-to-year variation in the catchability of the test fishery.

Daily test fishery index (C/f, number of fish caught per hour) is the average of the catches per hour for the two or three sets made each day, which runs for 24 h starting at 1700 h Pacific Daylight Savings Time.

Estimation of Weekly Abundance of Sockeye

To test the effects of weekly abundance on commercial fishery q and f, I required estimates of weekly escapement from Area 4 and estimates of their measurement error. Weekly escapement (E_w) was added to weekly commercial catch (C_w) to yield weekly stock abundance (N_w) available for harvest in Area 4 (Figure 4); I assumed that there is no pooling of sockeye in the commercial fishing area. If pooling occurs, it will tend to bias upward the estimates of harvest rate but should not bias the hypothesis tests (Appendix A). I did not include the Indian food fish catch from the commercial fishing area in N_w because I did not have estimates of the weekly catches by this fishery. However, this fishery harvests on average less than 1% of the annual abundance of sockeye in the commercial fishing area so I do not expect the results to be compromised by the omission. Weekly escapement was calculated from annual escapement and test fishery catch per effort data. The test fishery is located immediately upstream of the Area 4 fishing area so there is no migration lag from the fishing area to the test fishery (Appendix B). I assumed that the estimation error of the weekly catches is much smaller than that of the weekly escapements. Thus, the measurement error of weekly stock abundance (σ^2_{Nw}) is simply equal to that of weekly escapement (σ^2_{Ew}).

Weekly Escapement

I calculated the weekly escapement from the Area 4 fishery (E_w) using data from 1966-80 on the annual escapement of sockeye from Area 4 (E_y), cumulative annual catch per effort in the test fishery (C/f_y), and weekly catch per effort in the test fishery (C/f_w). I assumed that the ratio of weekly escapements (E_w) to weekly catch per effort (C/f_w) is the same as the ratio of those annual variables. Hence, to estimate weekly escapement:

$$E_w = (C/f_w) * E_y \; / \; (C/f_y) \tag{4}$$

Annual abundance of sockeye spawners in Area 4 and catches in Indian food fisheries between the test fishery and the Babine counting fence were summed to calculate the annual escapement of sockeye from Area 4.

Measurement Error of Weekly Escapement

The analyses below of sources of variation in commercial gillnet catchability and fishing effort use linear regression to estimate parameters and determine their significance. Regression is subject to bias when the independent variate is measured with error (Draper and Smith 1981). Estimates of the measurement error of weekly stock abundance can be used to correct the bias in linear regression, when weekly stock abundance is the independent variate. Since I do not have independent estimates of weekly abundance of sockeye at the test fishery site, I could not directly estimate the measurement error of the weekly escapements calculated from the test fishery data. Instead, I estimated this measurement error from the relationship between annual escapement of sockeye from Area 4 (E_y) and cumulative annual catch per effort in the test fishery (C/f_y) as follows. First, let

$$(5) \qquad E_y = 1/q_5 * (C/f_y) + v_5$$

where $1/q_5$ is determined by linear regression of E_y on C/f_y, constrained through the origin, and v_5 is a normally distributed random error term with variance σ^2_{v5}. Note that in the catch equation for the test fishery, stock abundance is actually escapement from the commercial fishing area, which gives the abundance of sockeye at the test fishery site. I will show in the next section, in my analysis of the effect of sockeye abundance on test fishery q, that the form of this equation is reasonable.

Assuming that $1/q_5$ is constant within and between years, then the weekly escapement (E_w) calculated from weekly C/f in the test fishery (C/f_w) is

$$(6) \qquad E_w = 1/q_5 * (C/f_w) + v_6, \text{ and}$$

$$(7) \qquad \sum_{w=1}^{n} E_w = \sum_{w=1}^{n} 1/q_5*(C/f_w) = 1/q_5 * \sum_{w=1}^{n} (C/f_w)$$

$$= 1/q_5*(C/f_y) = E_y,$$

where v_6 is a normally distributed random error term with variance σ^2_{v6} and n is the duration of the sockeye run in weeks.

Assuming that the error variances of the weekly escapement estimates are identical and independent of each other, then the error variance of the annual escapement estimate (σ^2_{v5}) is the sum of the error variances of the weekly escapement estimates,

$$(8) \qquad \sigma^2_{v5} = \sum_{w=1}^{n} \sigma^2_{v6},$$

and an estimate of the error variance of the estimate of weekly escapement calculated from the test fishery data is

$$(9) \qquad \sigma^2_{v6} = \sigma^2_{v5} / n.$$

Regressions of the log-transformed variates imply lognormally distributed, multiplicative measurement error. I estimated the variance of the multiplicative error term by regressing $\log_e(E_y)$ on $\log_e(C/f_y)$.

Statistical Issues

Testing the significance of parameters estimated by linear regression is confounded by errors in the independent variate which bias the slope toward zero (Draper and Smith 1981), i.e. downward for positive slopes and upward for negative slopes, and bias the intercept upward for positive slopes. I do not have independent, repeated estimates of the data values with which to calculate the ratio of errors in measuring the independent and dependent variates as required for the correction method of Richards and Schnute (1986) but I dealt with the problem of errors in variables in three ways. First, I used the geometric mean functional regression to estimate parameters since this method is less likely to reject the null hypotheses than ordinary least squares regression and it implicitly accounts for some unspecified measurement error (Ricker 1973). Second, I determined the variance of the measurement error in the independent variate above which the tests would incorrectly reject the null hypotheses (Peterman et al. 1985). Third, in those analyses where the independent variate is weekly stock abundance, I used my estimate of the measurement error variance of the reconstructed weekly stock abundance to correct the parameter estimates and their variances (Appendix C).

Specific Methods and Results

Test Fishery

H1a: Effect of Change in Net Material on q

To test the hypothesis that test fishery q changed in 1969 due to a change in net material, I used a t-test to test for differences in mean annual q before 1969 ($qbar_1$, 1966-68) and from 1969 on ($qbar_2$, 1969-1980). I found no significant change in the mean annual test fishery q associated with the change in net material in 1969 ($n_1=3$, $qbar_1=0.023$, $n_2=12$, $qbar_2=0.025$, $P(qbar_1=qbar_2)=0.7$).

H1b: Effect of Sockeye Abundance on q

I used annual data to test the hypothesis that test fishery q is density dependent by fitting

$$(10) \qquad C/f_y = a_{10} * E_y^{b10}$$

with linear regression of $\log_e(C/f_y)$ on $\log_e(E_y)$, where C/f_y is mean annual catch per effort, and testing the null hypothesis that $b_{10}=1$. If b_{10} is not significantly different from 1, this implies that C/f is linearly related to stock abundance and that q is density independent. Equation 10 is equivalent to equation 3 with escapement from the commercial fishing area (E_y) equal to N at the test fishery site and $q=a_{10}*N^{b10-1}$. If $b_{10}=1$, then $q=a_{10}$.

Regressions of the log-transformed variates (Equation 10) by both ordinary least squares (OLS) and geometric mean functional regression (GMF) were significant (n=15, OLS: $b_{10}=0.80$; GMF: $b_{10}=0.97$; OLS, GMF: $P(b_{10}=0)<0.001$), but the null hypothesis of density independent catchability was not rejected ($P(b_{10}=1)>0.8$). Tau b tests for heteroscedasticity of residuals were not significant (OLS: $\tau_b=0.22$, $P(\tau_b=0)=0.3$, GMF: $\tau_b=0.12$, $P(\tau_b=0)=0.6$). Modified Anderson-Darling tests (Stephens 1974) showed that the distributions of the residuals from the regressions were not significantly different from normality (OLS: mod $A^2=0.50$, $p(N)>0.15$, GMF: mod $A^2=0.29$, $p(N)>0.15$). Therefore, the assumption that test fishery C/f is linearly related to sockeye abundance is reasonable.

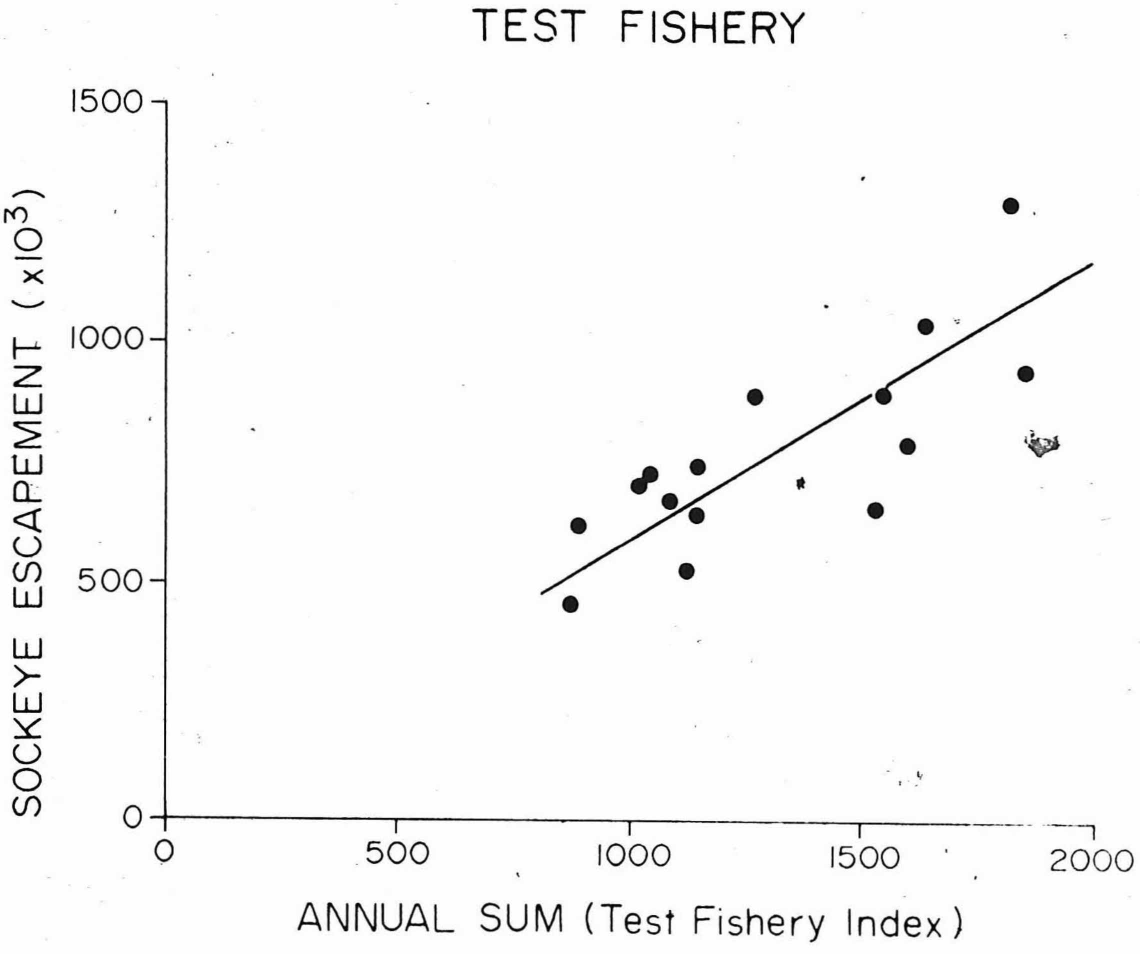
In order to calculate estimates of weekly escapement, I regressed annual escapement from Area 4 (E_y) on cumulative annual test fish index (C/f_y). The intercept (a) of this linear regression was not significant ($n=15$, $a=103{,}000$, $P(a=0)=0.5$) so I constrained the ordinary least squares regression through the origin. I found the slope (b) to be 589 ($P(b=0)=0.0001$) and the mean square error to be $1.7\text{X}10^{10}$ (Figure 7). These results confirm the form of equation 5, i.e. linear with no intercept. Since the test fishery operates for approximately 11 weeks each season during which 99% of the adult sockeye migrate, I estimated the additive measurement error (σ^2_{v6}) of the weekly escapement estimate to be $1.55\text{X}10^9$ (Equation 9). I calculated the lognormally distributed, multiplicative measurement error of $\log_e(E_y)$ for use with power models by regressing $\log_e(E_y)$ on $\log_e(C/f_y)$ ($n=15$, $P(b=0)=0.0004$) and found it to be 0.027.

Commercial Gillnet Fishery

H2a: Effect of Sockeye Abundance on q

To test for density dependence in the weekly q of the gillnet fleet, I fitted a power model to data on weekly gillnet catch per effort (C/f_w) and weekly stock abundance (N_w),

Figure 7. Annual abundance of sockeye at the site of the test fishery and annual sum of daily test fishery index (catch per hour).


TEST FISHERY

(11) $C/f_w = a_{11} * N_w^{b11}$

and tested the significance of the slope, i.e. $P(b_{11}=1)$. To test for possible interception by the gillnet fishery of sockeye bound for other areas, I also fitted a linear model to the functional response data

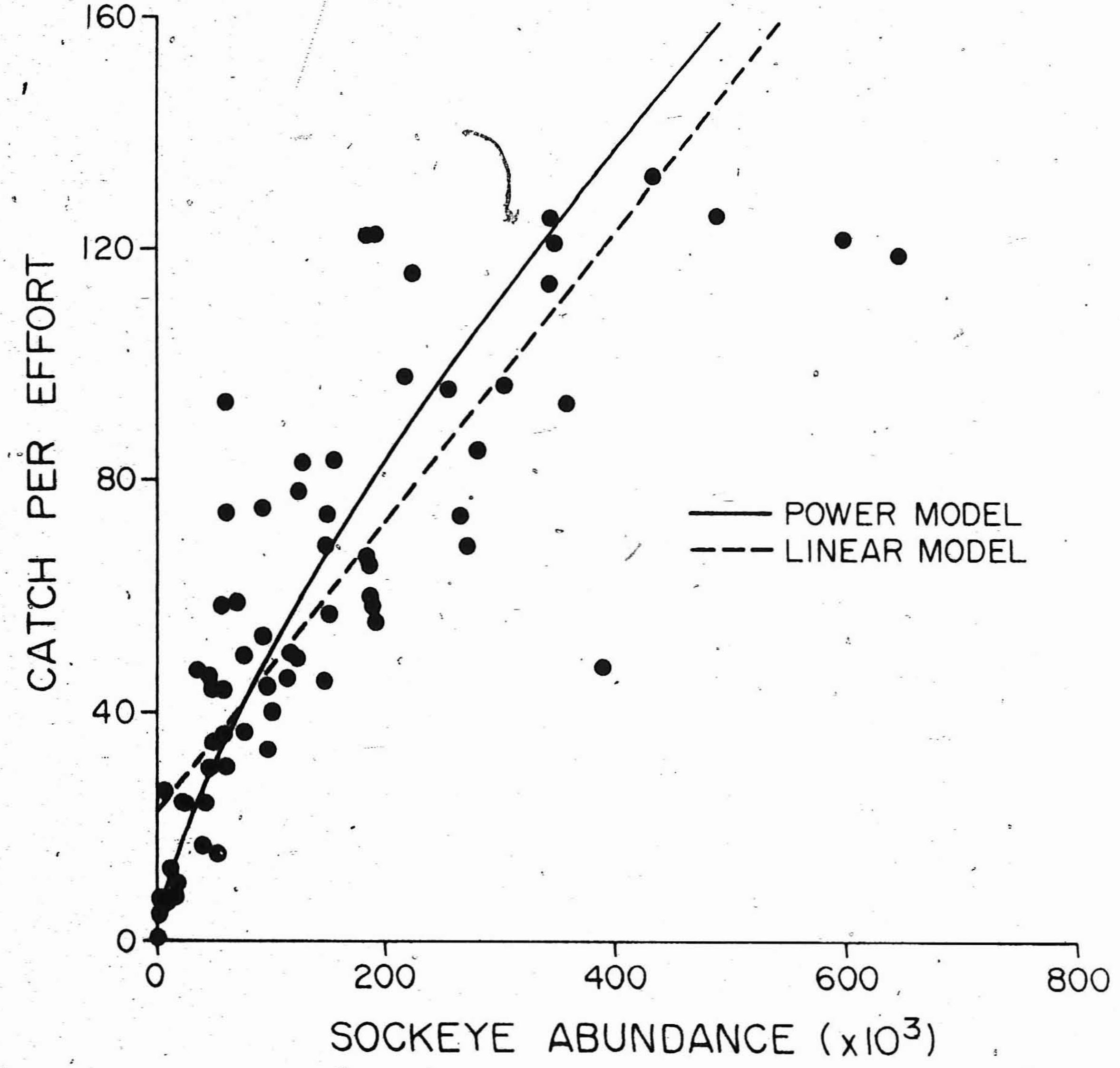
(12) $C/f_w = a_{12} + b_{12} * N_w$

and tested the significance of the intercept, i.e. $P(a_{12}=0)$. If the gillnet fishery intercepts sockeye bound for other areas, I would expect a positive intercept, reflecting the mean C/f of the intercepted stocks.

Regression of $\log_e(C/f_w)$ on $\log_e(N_w)$, the log-transformation of the power model (Equation 11, Figure 8), by OLS, GMF, and ordinary least squares corrected for measurement error (OLSc) were all significant (n=65, OLS: $b_{11}=0.67$, GMF: $b_{11}=0.77$, OLSc: $b_{11}=0.68$, OLS, GMF, OLSc: $P(b_{11}=0)<0.001$). All three fitting methods rejected the null hypothesis of density independent q (OLS, GMF, OLSc: $P(b_{11}=1)<0.001$). Catchability remained significantly density dependent even after I ran trials of the correction procedure with values of the measurement error of the estimated weekly abundance above the value I estimated from the test fishery data. The parameter estimates of the nonlinear functional response did not change significantly when data were stratified by length of fishery opening (Appendix D).

Figure 8. Weekly functional response of the Area 4 gillnet fishery, for 1966 - 1980. Power and linear models fitted by GMF regression. Catch per effort is catch per boat-day.

COMMERCIAL GILLNET FUNCTIONAL RESPONSE



Regressions of the linear model (Equation 12, Figure 8) using the three fitting techniques were also all significant (n=65, OLS $b_{12}=0.20X10^{-3}$; GMF $b_{12}=0.25X10^{-3}$; OLSc $b_{12}=0.22X10^{-3}$; OLS,GMF,OLSc: $P(b_{12}=0)<0.001$) with significant intercepts (OLS $a_{12}=30$; GMF $a_{12}=22$; OLSc $a_{12}=27$; OLS,GMF,OLSc: $P(a_{12}=0)<0.001$). The intercept remained significantly different from zero even when I tried values of the measurement error in the correction procedure above the level I estimated from the test fishery data. These intercepts correspond to intercepted stock abundances of 150,000 fish, 86,000 fish, and 127,000 fish for OLS, GMF, and OLSc, respectively.

I analyzed the residuals of $\log_e(C/f_w)$ from the log-transformed power model for time trends by regressing them first on year and then on week number (week 1 = first week in June, fishery week 6-1). Although I found no significant between-season time trend (b=-0.0033, P(b=0)=0.76), gillnet residuals decreased across weeks within seasons (b=-0.049, P(b=0)=0.005), i.e. the power model underestimates C/f early in the season and overestimates C/f late in the season. This within-season time trend in the residuals may result from fish pooling in the commercial fishing area (Appendix A). However, a linear model fit to these residuals explained only 12% of their variance. The power model explained 83% of the variance in the original relationship between the log-transformed variates, C/f and abundance. Therefore, I conclude that the effect on q of time is less important than the effect of sockeye abundance.

H2b: Effect of Fishing Effort on q

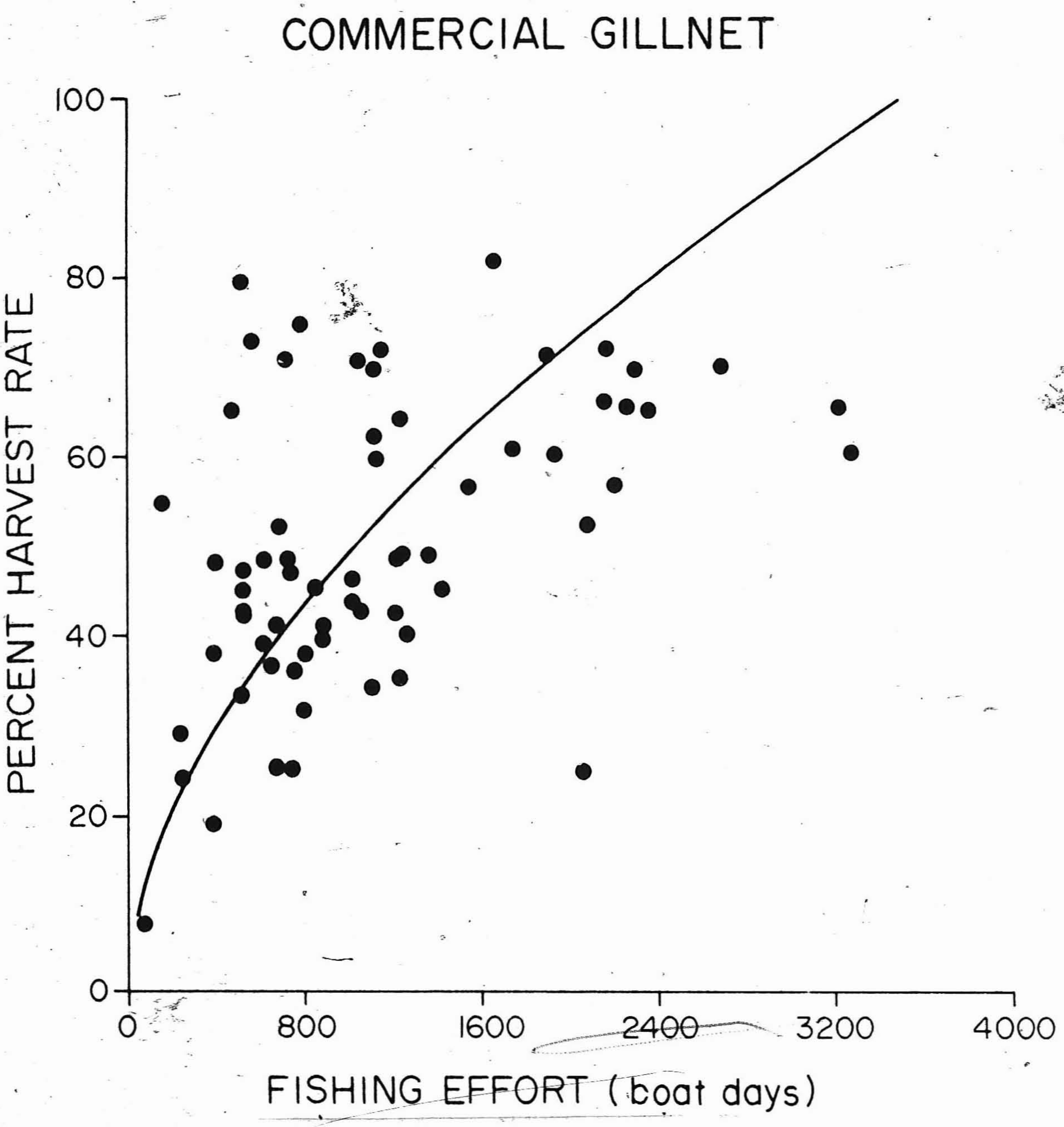
To test for the relative effects on weekly catchability of facilitation, and competition or attraction of less proficient fishermen, I fitted a power model to data on weekly harvest rate by the commercial gillnet fleet (C_w/N_w) and weekly gillnet fishing effort (f_w):

$$(13) \qquad C_w/N_w = a_{13} * f^{b13}$$

by regression of $\log_e(C_w/N_w)$ on $\log_e(f)$ and tested the hypothesis that q is dependent on nominal effort, i.e. $P(b_{13}=1)$. If it is greater than one, facilitation increases catchability and if the slope is less than one, competition at high effort levels or attraction of less proficient fishermen reduces catchability ($q = a_{13} * f^{b13-1}$).

OLS and GMF regressions of the log-transformed form of the relationship (Equation 13) between gillnet harvest rate and nominal effort (Figure 9) were significant (n=65, OLS: $b_{13}=0.33$, $P(b_{13}=0)<0.001$, GMF: $b_{13}=0.56$, $P(b_{13}=0)<0.001$) and significantly nonlinear (OLS, GMF: $P(b_{13}=1)<0.001$). The critical level of measurement error (s_e) in the estimate of effort above which the null hypothesis (H0: $b_{13}=1$) would be falsely rejected was 0.58. To put this in context, I calculated a 95% confidence interval on the geometric mean weekly gillnet effort (916 boat-days) as $\log_e(916)+/-1.96*s_e$ which, when exponentiated, produced lower and upper confidence bounds of 293 boat-days (-68% of the mean) and 2864 boat-days (312% of the mean), respectively. Although I do not have independent estimates of the measurement error of

Figure 9. Weekly gillnet harvest rate and nominal fishing effort (boat-days), for 1966 - 1980.


COMMERCIAL GILLNET
PERCENT HARVEST RATE
100
80
60
40
20
0
0
800
1600
2400
3200
4000
FISHING EFFORT (boat days)

weekly gillnet effort, it seems unlikely that the error was large enough to cause the true value to be outside of the 95% confidence interval, 293 to 2864 boat-days. Hence, it is unlikely that I falsely rejected the null hypothesis.

H3: Effect of Sockeye Abundance on Fishing Effort

Although I expect a relationship between average number of gillnet vessels fishing each week (f_w) and weekly sockeye abundance (N_w), I am not certain of its form. Therefore, I fitted both a power model

$$f_w = a_{14} * N_w^{b14} \tag{14}$$

using linear regression on the log-transformed variates and a linear model

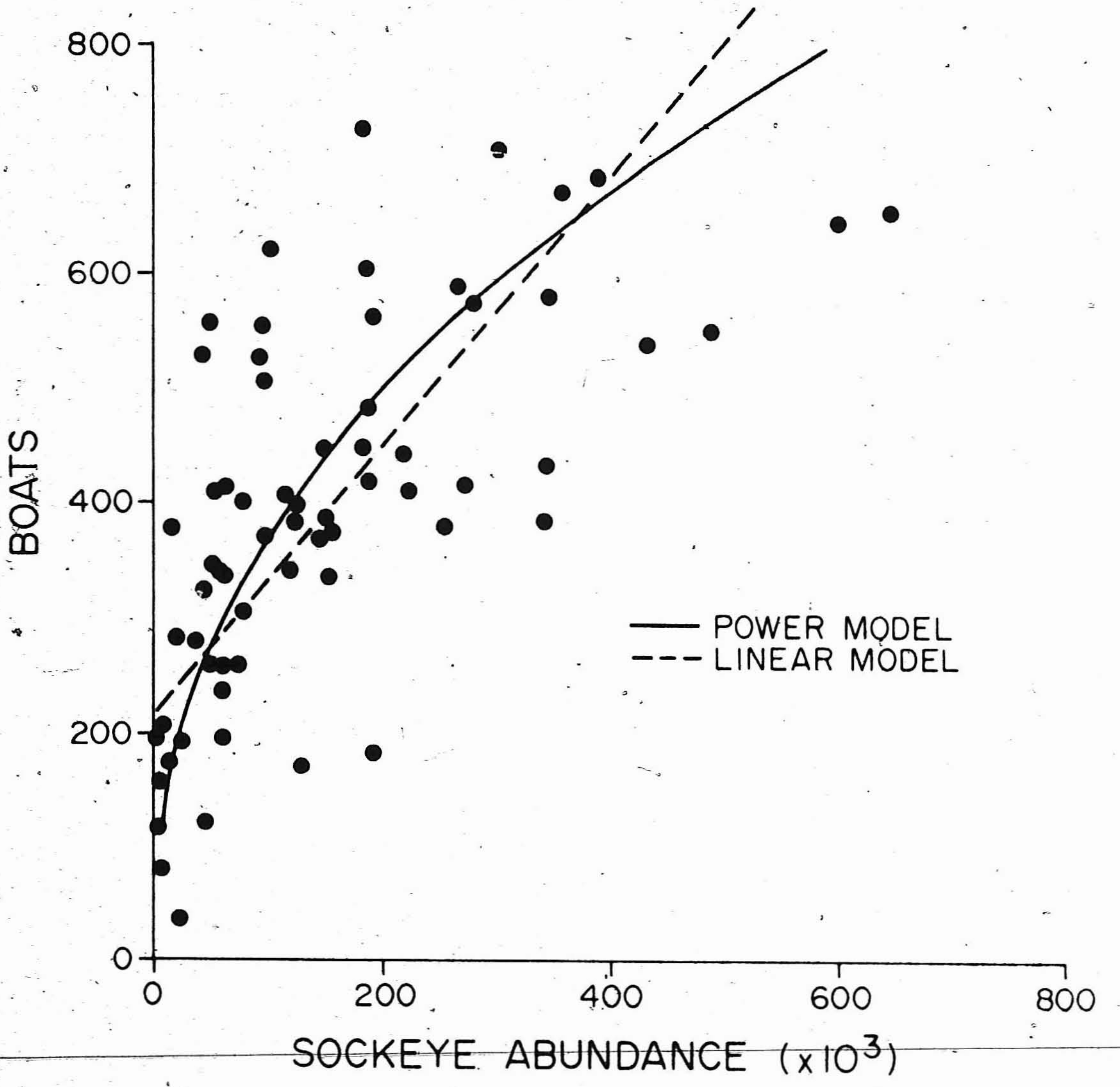
$$f_w = a_{15} + b_{15} * N_w \tag{15}$$

using linear regression. The presence of stationary and mobile components in the Area 4 gillnet fleet, the latter component responding to changes in stock abundance, would be reflected in a significant intercept in the linear model.

The gillnet fleet exhibits an aggregation response to weekly changes in sockeye abundance (Figure 10). Regressions of the natural log-transformed power model (Equation 14) using OLS, GMF, and OLS corrected for measurement error were all significant (n=65; OLS: $b_{14}=0.29$; GMF: $b_{14}=0.43$; OLSc: $b_{14}=0.30$; OLS, GMF, OLSc: $P(b_{14}=0)<0.001$) and significantly nonlinear, i.e. $b_{14}<1$ (OLS, GMF, OLSc: $P(b_{14}=1)<0.001$). The response

Figure 10. Weekly numerical response of the Area 4 gillnet fishery to changes in sockeye abundance. Power and linear models fitted by GMF regression. Boats is the average number of gillnet vessels fishing in each weekly fishery opening.

COMMERCIAL GILLNET NUMERICAL RESPONSE



remained significantly density dependent when I ran trials with the measurement error of the estimated weekly abundance above the level I estimated from the test fishery data.

Regressions of the linear model (Equation 15) using the three fitting methods were all significant ($P<0.001$) with significant, positive intercepts (OLS: $a_{15}=278$, GMF: $a_{15}=217$, OLSc: $a_{15}=269$; OLS, GMF, OLSc: $P(a_{15}=0)<0.001$). A positive intercept could indicate a group of resident gillnet vessels that do not respond to changes in sockeye abundance but fish anyway. The intercept remained significant at levels of measurement error of stock abundance above the level I determined for the test fishery. The correlation coefficient of the power model ($r=0.67$) was similar to that of the linear model ($r=0.66$).

To distinguish whether the linear or power model was most appropriate, I examined their residuals. Tests of residuals from the power model fitted by OLS showed significant heteroscedasticity ($\tau_b=-0.20$, $P(\tau_b=0)=0.02$) and deviations from the normal distribution (mod $A^2=2.03$, $P(N)<0.01$). Residuals from the linear model were homoscedastic ($\tau_b=-0.02$, $P(\tau_b=0)=0.8$) and normally distributed (mod $A^2=0.031$, $P(N)>0.15$). To test for time trends in the residuals from the power and linear models, I regressed their residuals first on week number and then on year. I found significant within-season time trends for residuals from the OLS fit ($b=0.05$, $P(b=0)=0.005$) to the power model indicating that this model tends to underestimate effort late in the season. The linear model exhibited no within-season time trends

($b=6.7$, $P(b=0)=0.3$). There were no significant between-season time trends in residuals from the power model (OLS: $b=-0.015$, $P(b=0)=0.2$) or in those from the linear model ($b=-6.1$, $P(b=0)=0.08$). Therefore, I conclude that the linear model is better than the power model for describing the in-season aggregation response of the gillnet fleet.

Test Fishery and Commercial Gillnet Fishery

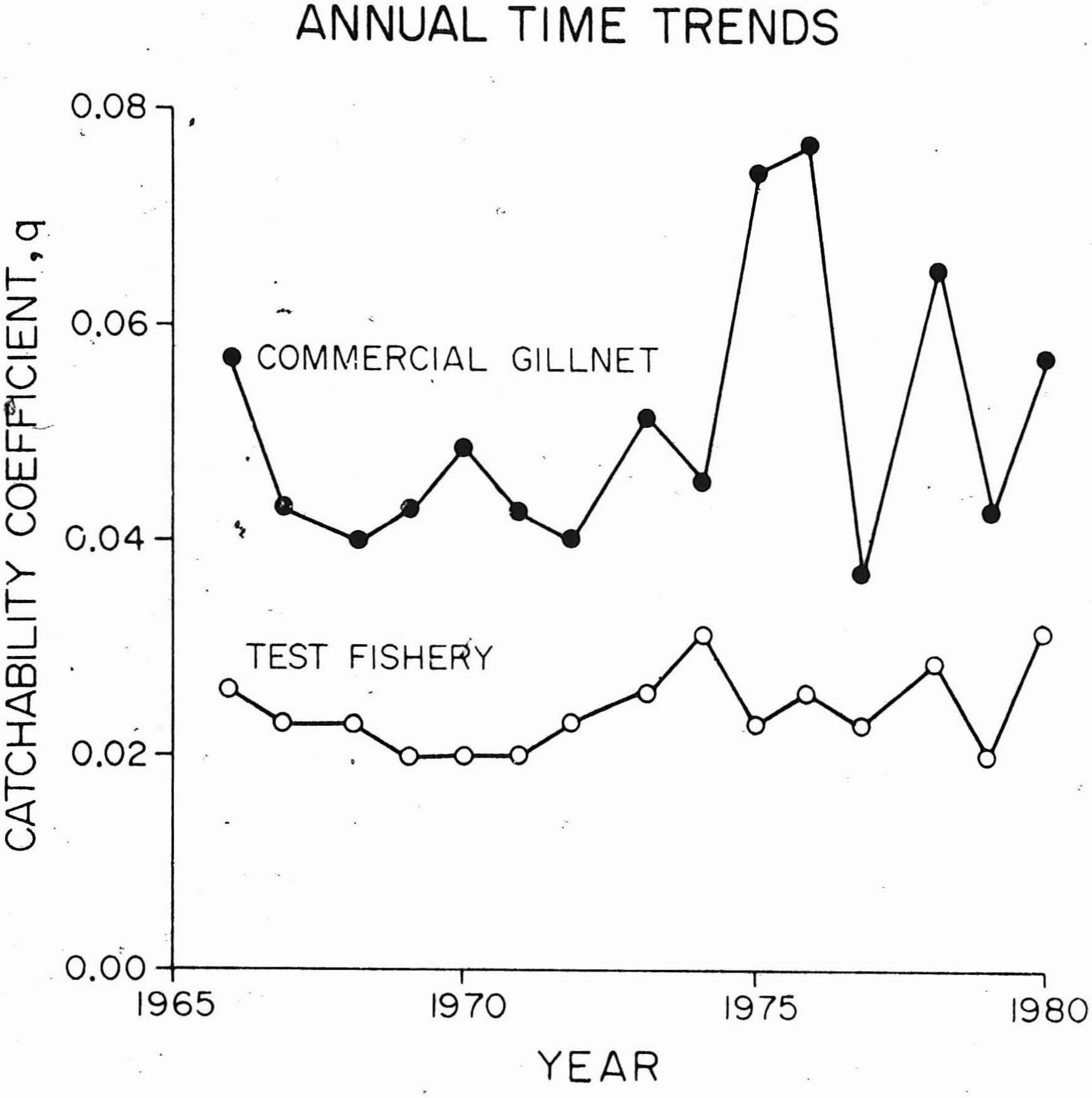
H1c: Effect of Time on Test Fishery q

H2c: Effect of Time on Commercial Gillnet q

To test for time trends in the catchability coefficient of the Area 4 commercial gillnet fleet, I used analysis of covariance to test the hypothesis that the slope of the regression of annual gillnet q on year was significantly different from the slope of the regression of annual test fishery q on year. I used annual data because I did not have independent estimates of weekly escapement from Area 4 with which to calculate weekly catchability coefficients for both the gillnet and test fisheries.

Regressions of annual test fishery q on year ($n=15$, $b_{TF}=0.0004$, $P(b_{TF}=0)=0.1$) and annual gillnet fishery q on year ($n=15$, $b_{GN}=0.0008$, $P(b_{GN}=0)=0.3$) were not significant. The slope of the regression between annual gillnet catchability and year (Figure 11) was not significantly different from that for the test fishery ($P(b_{TF}=b_{GN})>0.55$). The absence in this

Figure 11. Time trends in annual gillnet q and in annual test fishery q.


ANNUAL TIME TRENDS
CATCHABILITY COEFFICIENT, q
0.08
0.06
0.04
0.02
0.00
COMMERCIAL GILLNET
TEST FISHERY
1965
1970
1975
1980
YEAR

analysis of a time trend in gillnet catchability is supported by my finding above that residuals from the regression analysis of the weekly gillnet functional response did not exhibit an annual time trend.

H4: Correlation of Test Fishery q and Commercial Gillnet q

I correlated annual gillnet q with annual test fishery q to test the relative importance of the effects on q of environmental and biological factors, such as fish behaviour, common to both fisheries, versus factors such as fishery regulations, changes in fishermen behaviour or changes in gear, that affect only the gillnet fishery. If common environmental and biological factors are important, I would expect the catchability coefficients to be significantly correlated. Annual gillnet catchability and annual test fishery catchability were not significantly correlated (n=15, r=0.37, P(r=0)=0.2).

Discussion

I found in my analysis of variations in fishing effort, f, that during the fishing season, the number of commercial gillnet vessels fishing in Area 4 was correlated with sockeye abundance, N. This result is not unexpected given that others have found relationships between fishing effort and indices of abundance such as catch (Botsford et al. 1983, Hyatt and Steer 1987) or catch per effort (Walters and Buckingham 1975, Hilborn and Ledbetter 1979, Peterman et al. 1979, Argue et al. 1983, Millington 1984). The relationship between vessel abundance and

N also did not change over the study period, 1966 to 1980; residuals from either the linear model or the power model did not exhibit trends over years. This last result is due to the limited entry program in 1969 which attempted to limit the number of fishing vessels on the B.C. coast (Pearse and Wilen 1979).

The form of the aggregation response of the Area 4 gillnet fleet appears to be linear with a positive intercept rather than nonlinear, suggesting a group of fishermen that do not respond to changes in stock abundance but always fish Area 4. The intercept indicates that 217 to 2~~7~~38 vessels will fish Area 4 when the abundance of the stock is zero. This number is not due solely to the presence of a group of fishermen who only fish Area 4. From 1979 to 1981, only 51 vessels on average fished solely in Area 4 (Millington 1984). The additional 200 vessels likely fished Area 4 on the expectation of harvestable quantities of sockeye based on their previous experience in the area (Walters and Buckingham 1975) and also implied by the opening of the fishery by the fishery managers.

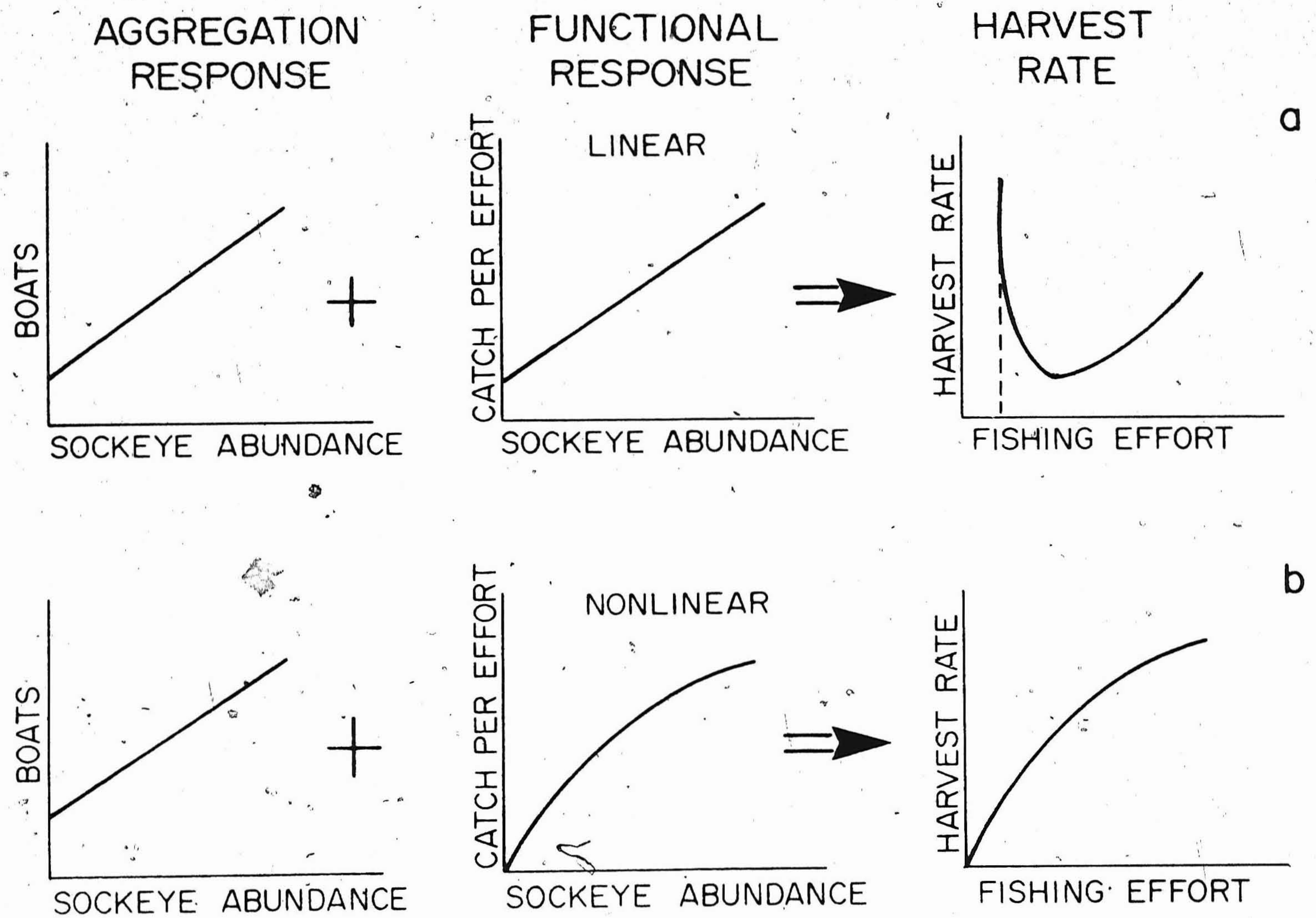
I found in my analysis of sources of variation in the catchability coefficient of the commercial gillnet fleet that harvest rate of sockeye (C/N) was nonlinearly related to nominal fishing effort. This result is similar to the findings of others. Brannian (1982) found that the same power model gave the best fit to q and f data from the sockeye fishery in Togiak Bay, Alaska. Walters and Buckingham (1975) fitted an asymptotic curve to harvest rate and fishing effort data from the 1971-73 sockeye fisheries on the Skeena River.

I also found that either (1) q was density dependent or (2) q was density independent and the fishery intercepted significant numbers of sockeye bound for other areas. However, since I found a nonlinear relationship between harvest rate and effort and a linear relationship between vessel abundance and stock abundance, q cannot be density independent as implied by the interception model. The forms of the relationships are inconsistent (Figure 12a). This finding is explained as follows. From the analysis of vessel abundance and sockeye abundance, I found that between 217 and 278 vessels would fish when the reconstructed abundance of sockeye was zero. From the analysis of catchability and sockeye abundance, I found that the linear model predicted between 22 and 30 fish would be caught per boat-day at very low abundance levels. The fisheries were open for one or two days at these low levels of stock abundance, so these two relationships imply that apparent harvest rate would approach 100% near a level of nominal fishing effort equal to 217 to 278 boat-days (1 day open) or 434 to 556 boat-days (2 days open). However, apparent harvest rate does not increase at low effort levels (Figure 9). The forms of the harvest rate response and the aggregation response are consistent with density-dependent q (Figure 12b) so I conclude that q is density dependent.

Figure 12. Form of relationship between harvest rate and fishing effort that would result from a linear relationship between number of gillnet vessels and stock abundance (aggregation response) and,

a. linear relationship between catch per effort and sockeye abundance (linear functional response), or

b. nonlinear relationship between catch per effort and sockeye abundance (nonlinear functional response).


AGGREGATION RESPONSE
FUNCTIONAL RESPONSE
HARVEST RATE
a
BOATS
SOCKEYE ABUNDANCE
+
CATCH PER EFFORT
LINEAR
SOCKEYE ABUNDANCE
HARVEST RATE
FISHING EFFORT
b
BOATS
SOCKEYE ABUNDANCE
+
CATCH PER EFFORT
NONLINEAR
SOCKEYE ABUNDANCE
HARVEST RATE
FISHING EFFORT

The presence of an aggregation response results in three possible mechanisms for the apparent density dependence in q. In the first mechanism, all gillnet vessels have the same catchability coefficient but q depends on stock abundance, possibly because vessels are more efficient at finding schools of fish when the stock is less abundant (Paloheimo and Dickie 1964, Peterman and Steer 1981, Winters and Wheeler 1985, Crecco and Savoy 1985). In the second mechanism, q is again the same for all vessels but it depends on effort, possibly because vessels interfere with each other at high effort levels (Walters and Buckingham 1975, Rothschild 1977, Brannian 1982, Ledbetter 1983), which are associated with high stock abundance. In the third mechanism, gillnet vessels have different catchability coefficients. The "area specialists" (Hilborn 1985a) fishing at low stock abundance have a higher catchability than the "movement specialists" attracted by increases in stock abundance. Unfortunately, I was unable to distinguish among these three mechanisms because to do so requires catch and effort data for individual vessels.

Fishery managers often assume that there is no long term time trend in the average efficiency of commercial fishing vessels. Analysis of the annual catchability coefficient of the Area 4 gillnet fleet and of the residuals from the weekly functional response of this fleet from 1966 - 1980 support this assumption on average; there was no trend to increased efficiency with time. Capital growth, which occurred at an annual rate of 5.7% from 1957 to 1968 and 3.7% from 1969 to 1977 (Pearse and Wilen

1979) and resulted in more powerful and larger gillnet vessels (Fraser 1979), did not increase gillnet catchability, which is the proportion of the sockeye population caught per gillnet boat-day. Either the investments were not effective or their effectiveness was counteracted by fisheries regulations. In either case, these investments simply increased costs and did not increase the number of sockeye caught per boat-day.

These results have important implications for fishery management. If the fishery manager assumes constant q in the catch equation (C=qfN), then the apparent dependence of commercial gillnet q on nominal effort or stock abundance can result in overharvest at low levels of effort or stock abundance. The manager will overestimate the length of fishery opening required to harvest the desired catch and will overestimate the annual abundance of fish that are subject to harvest. Because q increases at low abundance, the fishery will harvest more fish than predicted by a linear model between C/f and abundance, which assumes constant q. Also, if C/f is nonlinearly related to abundance, declines in C/f will underestimate declines in stock abundance thus masking overharvest (Gulland 1977, Clark and Mangel 1979, Peterman and Steer 1981). Finally, this depensatory mortality effect of the fishery could lead to stock extinction either directly, if the effect results in critical depensation (Clark 1974, Gulland 1977, Clark and Mangel 1979), or indirectly, if it reduces the resilience of the stock (Holling 1973) and thus makes the population vulnerable to stochastic environmental effects (Clark 1974).

The finding of an aggregation response by the Area 4 gillnet fleet is important for determining the benefits due to enhancement projects. The benefits from these projects may be reduced by the attraction of additional vessels to a fishing area. Smaller net economic benefit could arise from additional costs of movement to the fishing area and from higher costs of harvest resulting from interference competition or the relative inefficiency of the additional vessels.

The low correlation between test fishery q and commercial fishery q suggests that the regulatory and technological factors that affect commercial gillnet q are more important in causing interannual variation in q than are environmental and biological factors common to the test and commercial fisheries. The annual catchability coefficient of the test fishery is less variable than that of the commercial fishery (Figure 11) because test fishery procedures and gear are rigorously standardized. Reduced variability in q should result in more precise estimates of stock abundance from test fishery catch per effort data than from commercial fishery catch per effort data. The catchability coefficient of the commercial fishery is the net result of the interaction between regulations that decrease q and improvements in fishing technology and procedures that increase it. Temporary imbalances between these factors contribute to higher interannual variation in the commercial gillnet catchability coefficient over time and thus destroy any relationship between commercial gillnet q and test fishery q.

III. Value of a Test Fishery to Management of a Commercial Gillnet fishery for Sockeye Salmon (*Oncorhynchus nerka*) Introduction

In this chapter, I use a simulation model to calculate the net benefit of test fishery data to management of the commercial gillnet fishery for sockeye in Area 4. I determine if the benefit of using this information exceeds the cost of its acquisition, i.e. is the test fishery economic? The benefit of test fishery information is the difference between the total benefit from the commercial fishery managed using test fishery information, measured as mean annual value or net present value of the commercial harvest, and the total benefit from the fishery managed without the test fishery data. In the latter case, it is managed using the next best alternative in the absence of test fishery information. The cost of test fishery information is simply the additional cost to the Canada Department of Fisheries and Oceans of operating the test fishery. Assuming that management objectives are set to maximize benefits, improving the information available for managing the fishery should reduce deviations from these objectives and increase benefits. Annual deviations from objectives result from 1) errors in forecasts of annual abundance of returns which are used to set weekly objectives during the season, and 2) from errors in controlling the fishery to meet those weekly objectives.

I estimate the benefits to the fishery resulting from management based on three types of simulated fishery information systems. These systems are classified by type of information used to forecast annual abundance of sockeye returns:

(1) PRE - Return forecast based on pre-season data only.

(2) COMM - Return forecast based on pre-season data and commercial fishery catch per effort (C/f).

(3) TEST - Return forecast based on pre-season data, commercial fishery C/f, commercial catch, and test fishery C/f.

I evaluated the benefits of both PRE and COMM information because it is not clear a priori which is the next best alternative to TEST information. Although commercial fishery data are often used as indices of stock abundance (Brannian 1982, Steer and Hyatt 1987), Henderson et al. (1987) have shown that the prediction error of return forecasts based on commercial fishery C/f may be about the same as that of return forecasts based on pre-season data. I extended the analysis of Henderson et al. (1987) to calculate the prediction error of forecasts of sockeye abundance in Area 4 and then used simulation to estimate the economic benefit of improved precision of return forecasts. Of the PRE and COMM management schemes, the one that has the highest total benefit is defined as the next best alternative. This criterion is equivalent to net total benefit because the costs of the two management schemes are approximately equal; the additional information required for COMM management is collected incidentally to the enforcement of fishery regulations to control weekly harvest. I assume that both PRE and COMM management are economically efficient, i.e. total benefits exceed total costs. Total benefit of the next best alternative is subtracted from that resulting from TEST management to yield an estimate of the benefit of test fishery data. If this benefit exceeds the cost of operating the test fishery, then management based on test fishery data is economically efficient.

Each simulated management scheme consists of two parts, one to forecast the abundance of the sockeye stock and another to control the harvest to meet management objectives. Details of the algorithms used to simulate each of the three management systems are presented in the Management Submodel section below, but briefly they are as follows. The PRE system requires the least amount of data of the three and uses only a pre-season forecast to estimate annual abundance of returns. This forecast of annual abundance of returns is used in conjunction with an annual escapement objective to determine the annual catch objective. This system then uses cumulative catch to date within the season, historical C/f data, and estimates of vessel abundance to set the duration of subsequent openings and achieve the annual catch objective. The COMM system uses weekly C/f data from the commercial gillnet fishery and the historical relationship between annual abundance of returns and cumulative C/f to forecast annual abundance of returns from in-season data. This forecast is combined with the pre-season forecast to produce a revised forecast of returns which is then used to calculate the annual and weekly catch objectives. The TEST system requires the most data of the three systems and uses cumulative commercial catch, cumulative C/f data from the test fishery, and the historical relationship between annual abundance of returns and cumulative test fishery C/f to forecast annual stock abundance. This forecast is combined with the pre-season forecast and the in-season forecast based on commercial fishery C/f to yield a revised forecast of annual returns which is then used to revise the catch objective in a given week.

Methods

The model consists of four submodels: (1) sockeye population dynamics, (2) fishing fleet dynamics, from the analysis in the previous chapter, (3) management, and (4) economic. The management submodel simulates the action of fishery managers in forecasting abundance of returns and opening fisheries in response to fishing fleet dynamics and sockeye population dynamics, which are both stochastic. The economic submodel calculates benefits and costs throughout each simulation and discounts the annual values to give net present value. The model is run 100 times for each of the three management systems using different random number series for the stochastic components in each of the simulations. The benefit of the test fishery is the difference between the mean annual value of the commercial harvest when the fishery is managed using test fishery data, and the corresponding value when it is managed without test fishery data. The benefit is then compared with the cost of acquiring test fishery information. The four components of the model are described below.

Sockeye Population Dynamics Submodel

The population dynamics component simulates total returns resulting from annual abundance of spawners, divides this brood year production into returns at each age, and simulates the weekly abundance of sockeye returns during the fishing season (Figure 13).

Abundance of Returns (Stock-recruitment)

To simulate total abundance of returns (R) from annual abundance of spawners (S), I use a Ricker stock-recruitment function (Ricker 1975) with a lognormal error term (Peterman 1981):

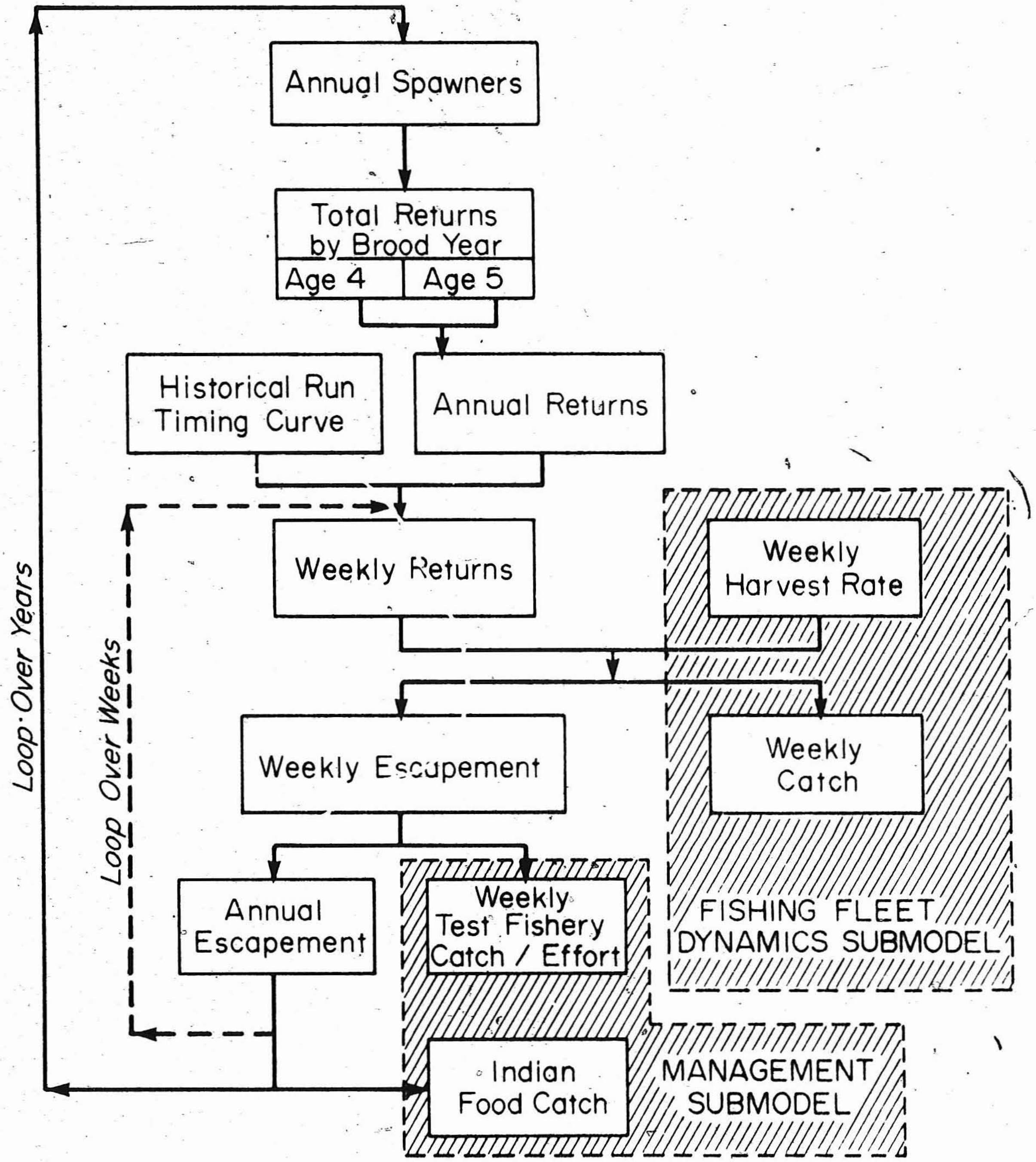
$$(1) \qquad R = S * e^{a1(1-S/Sr) + v1}$$

where a_1 is a productivity parameter, S_r is the equilibrium stock size in the absence of harvest, and v_1 is a normally distributed random error term with variance σ^2_{v1}. The parameters were estimated by least squares regression of the natural log linear form of the above function

$$(2) \qquad \ln(R/S) = a_1 - a_1/S_r*S + v_1$$

Figure 13. Flow chart of Sockeye Population Dynamics Submodel. and its relationship to Fishing Fleet Dynamics and Management Submodels.

SOCKEYE POPULATION DYNAMICS SUBMODEL



fitted to data on annual catch and escapement at age for sockeye returning to Area 4 from brood years 1951 to 1975 (Data from Peterman (1982) and from R. Kadowaki, Department of Fisheries and Oceans (DFO), Prince Rupert, B.C., personal communication). I found a_1=1.07, S_r=1.67X10^6 and σ^2_{v1}=0.32. Although the slope ($b=a_1/S_r$) of the relationship was not significant (n=25, P=0.25), the point estimates of the parameters and variance are sufficient for the purposes of this model to realistically simulate recruits produced by different abundances of spawners. To start the simulations, I used actual annual escapements from 1976 to 1980 (Table 2).

One assumption of this analysis is that the parameter values of the stock-recruitment function did not change from 1951 to 1975 in spite of a series of enhancement initiatives during this period. These activities could produce a systematic change in parameter values which would inflate the error sum of squares and could render the regression not significant. To enhance sockeye production, two spawning channels were completed on the Fulton River in 1965 and 1971 and one on the Pinkut River in 1968 (West 1978). Also, dams to control water flow were completed on the Fulton River in 1968 and on the Pinkut River in 1966. Although these projects were completed over several years, fry output from the two systems increased substantially in 1971. To test for a systematic change in stock-recruitment parameter estimates due to these enhancement initiatives, I used analysis of covariance to test the hypothesis that the linearized stock-recruitment function before brood year 1970 was

Table 2. Initial abundances of spawners in simulation model. Data are abundances of Skeena spawners, 1976-80.

Year	Spawners
1976	583000
1977	951000
1978	421000
1979	1168000
1980	543000

not different from that from 1970 on. I found no significant difference ($F_{2,21}=0.54$, $P=0.59$) and conclude that although there may be a change in parameter values due to enhancement, it is masked by random variation due to environmental factors.

Age at Return

Although adult sockeye return to spawn and thus recruit to the fishery at age 3, 4, 5 or 6 years, the majority return to Area 4 at ages 4 and 5 in about equal proportions. The average proportion of total returns from brood years 1951 through 1975 was 0.48 at age 4 and was 0.49 at age 5. To simplify calculations, I assume in the simulation that returns from each brood year are split evenly between age 4 and 5 only. Therefore, annual abundance of returns to the fishery in a given calendar year, y, consists of half of the returns from the escapement 4 years previous (R_{y-4}) and half of the returns from the escapement 5 years previous (R_{y-5}):

$$N = 0.5 * R_{y-4} + 0.5 * R_{y-5} \tag{3}$$

Timing of Returns

To simulate weekly abundance of sockeye returns in the fishery in week t (NW_t), the model randomly selects an annual run timing curve j from the set of historical timing curves that I calculated from Area 4 sockeye catch, escapement and test fishery data (Table 3), and multiplies the simulated annual abundance of returns (N) by the weekly proportion of annual returns ($p_{t,j}$) from the timing curve:

Table 3. Sockeye return timing data. Proportion of annual return of Area 4 sockeye that returned each week, 1966-80, reconstructed from annual escapement, weekly test fishery index and weekly catch data. Week 1 is fishery week 6-2, the second week in June.

			Year			
Wk	**1966**	**1967**	**1968**	**1969**	**1970**	**1971**
1	0	0	0.002	0.004	0.002	0
2	0.005	0.008	0.060	0.035	0.007	0.004
3	0.023	0.010	0.041	0.035	0.040	0.004
4	0.044	0.045	0.113	0.048	0.062	0.013
5	0.068	0.069	0.068	0.120	0.121	0.026
6	0.239	0.156	0.389	0.151	0.183	0.086
7	0.078	0.212	0.198	0.216	0.150	0.217
8	0.327	0.249	0.094	0.148	0.099	0.198
9	0.151	0.164	0.030	0.183	0.203	0.174
10	0.042	0.059	0.005	0.033	0.120	0.205
11	0.018	0.019	0.001	0.022	0.011	0.056
12	0.005	0.009	0	0.005	0.002	0.017

			Year			
Wk	**1972**	**1974**	**1977**	**1978**	**1979**	**1980**
1	0	0	0	0	0.016	0.013
2	0.003	0.023	0.011	0.037	0.016	0.034
3	0.023	0.033	0.011	0.026	0.020	0.056
4	0.021	0.045	0.051	0.079	0.027	0.102
5	0.036	0.103	0.068	0.158	0.088	0.183
6	0.041	0.174	0.180	0.274	0.197	0.191
7	0.280	0.243	0.259	0.205	0.262	0.126
8	0.156	0.277	0.243	0.123	0.157	0.190
9	0.254	0.085	0.144	0.053	0.175	0.064
10	0.136	0.013	0.028	0.026	0.037	0.034
11	0.044	0.004	0.004	0.015	0.005	0.005
12	0.006	0	0.001	0.004	0	0.002

(4) $NW_t = N * p_{t,j}$

I did not use timing data from 1973, 1975 or 1976 because I had difficulty assigning catch to a week due to strikes by fishermen or inconsistencies in the data (e.g. vessels counted but no catch reported).

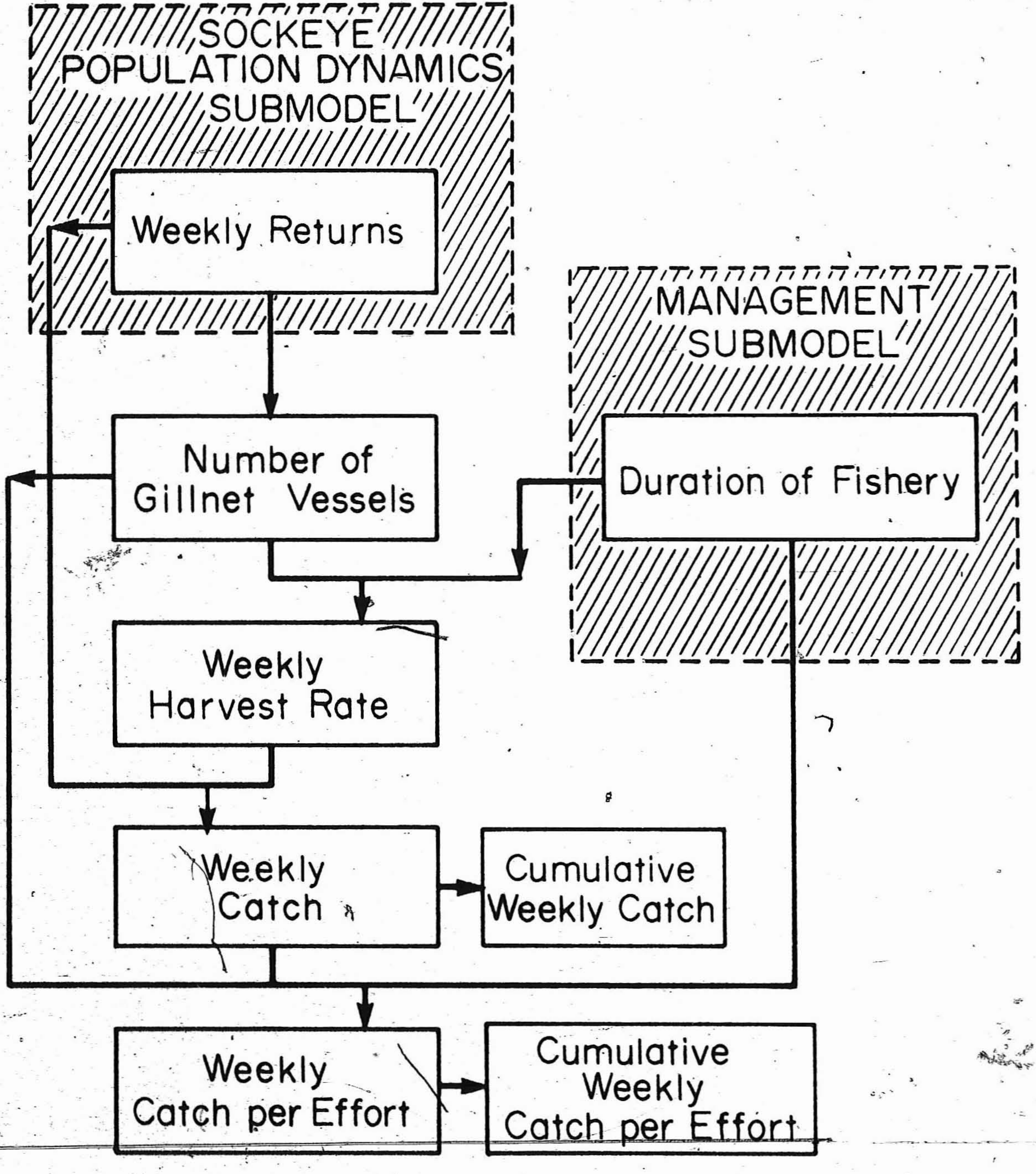
Two assumptions of this algorithm are that return timing is independent of abundance of returns and that it does not systematically vary across years. Therefore, I tested the hypotheses that (1) mean time of return is correlated with magnitude of the run, (2) mean time of return is correlated with year, (3) standard deviation of time of arrival is correlated with magnitude of the run, and (4) standard deviation of time of arrival is correlated with year, by regressing these simple statistics on abundance of annual returns and on year. None of the four regressions were significant (n=12, all $P>0.1$).

Fishing Fleet Dynamics Submodel

Using the relationships that I derived in the previous chapter, the fishing fleet dynamics component simulates abundance of gillnet vessels in response to simulated weekly stock abundance and simulates harvest rate in response to simulated weekly fishing effort (Figure 14).

Figure 14. Flow chart of Fishing Fleet Dynamics Submodel and its relationship to the Sockeye Population Dynamics and Management Submodels.

FISHING FLEET DYNAMICS SUBMODEL



Number of Gillnet Vessels

To simulate the number of gillnet vessels (GNW_t) fishing in each weekly fishery, I use the simulated weekly abundance of sockeye (NW_t) and the linear relationship between average number of gillnet vessels per week and weekly abundance of sockeye:

$$(5) \qquad GNW_t = \text{MAX of} \begin{cases} 280 + 0.00076 * NW_t + v_5 \\ 30 \end{cases}$$

where v_5 is a normally distributed random error term with variance $\sigma^2_{v5}=16000$. Parameters were estimated in the previous chapter (Figure 10) in the ordinary least squares regression analysis of the effect of sockeye abundance on variations in fishing effort. At low abundance levels, it is possible for this function to generate vessel abundances less than 0 because of the variance term, v_5, so I set a minimum of 30 vessels. This is approximately equal to the minimum number of gillnet vessels that fished only in Area 4 from 1979-81 (Millington 1984).

Harvest Rate

I use the asymptotic relationship between harvest rate and weekly gillnet fishing effort derived in the previous chapter (Figure 9) to simulate the harvest rate in week t (MW_t) from simulated weekly abundance of vessels (GNW_t) and duration of the weekly fishery ($DAYS_t$):

$$(6) \qquad MW_t = \text{MIN of} \begin{cases} 0.05 * (GNW_t * DAYS_t)^{0.33} * e^{v6} \\ 0.95 \end{cases}$$

where v_6 is a normally-distributed random error term with variance $\sigma^2_{v6}=0.11$. I use the harvest rate function because it integrates the potential effects on q of both fishing effort and sockeye abundance. The effect of sockeye abundance on q is included in this function because vessels respond to changes in sockeye abundance in the model. Parameters of the harvest rate function were estimated in the previous chapter in the ordinary least squares regression analysis of the effect of nominal fishing effort on commercial gillnet catchability. At high effort levels it is possible for this function to generate exploitation rates greater than 1 because of the variance term, so I set a maximum harvest rate of 95%.

Management Submodel

The salmon management process consists of setting objectives such as annual abundance of escapement and proportion of catch by gear type, forecasting the total abundance of returns of sockeye subject to harvest, and then controlling the timing and duration of fishery openings to meet these objectives. In the model, I simplify this management process slightly by considering only the gillnet harvest sector, the major harvester of sockeye in Area 4 from 1965 through 1980. This eliminates the requirement in the model for allocation among gear types and reduces the management problem to one of controlling catch by one gear type over a series of openings to meet an annual escapement target.

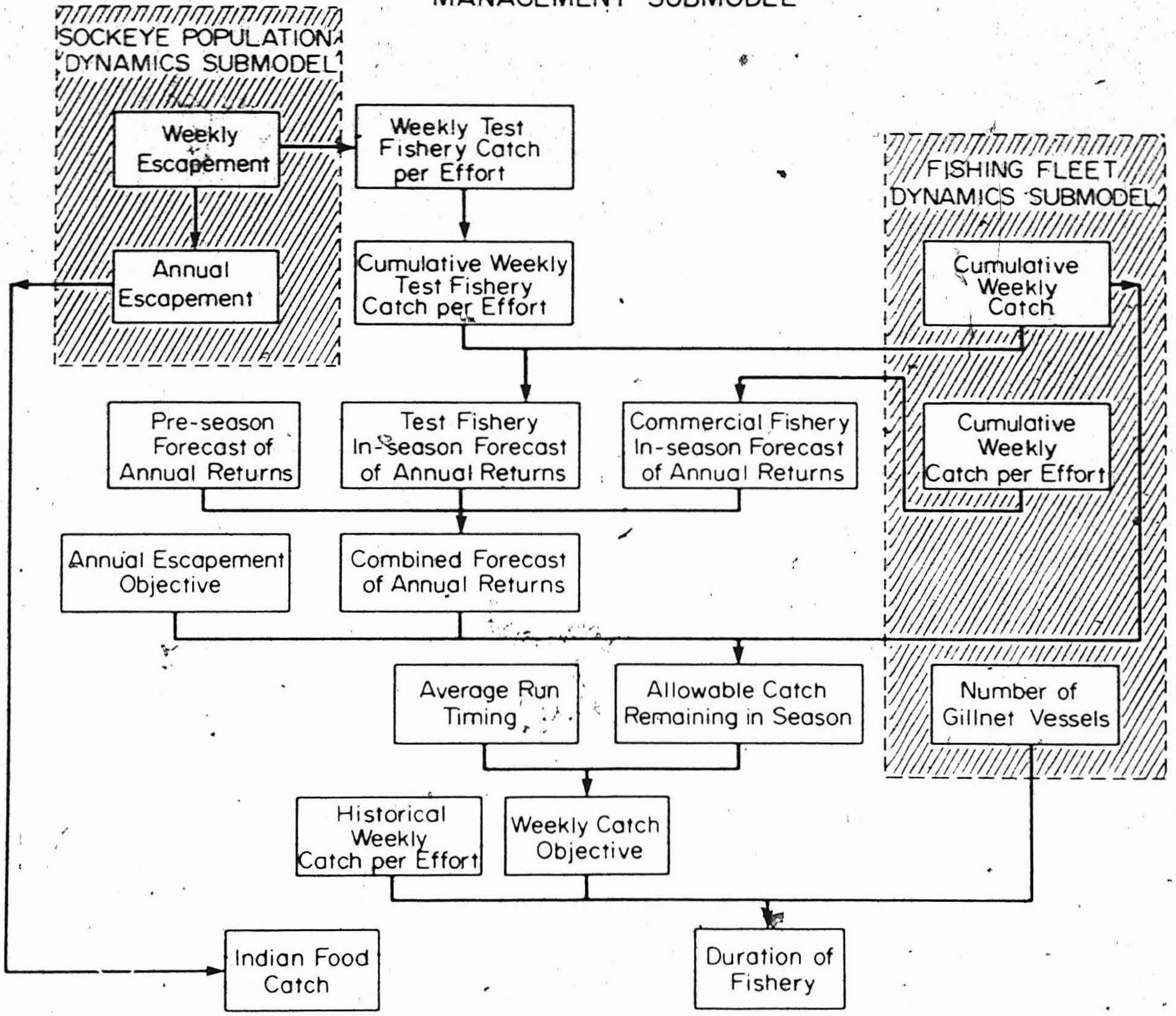
In the management component of the model, the management process is broken down into a series of steps (Figure 15). The model simulates pre-season and in-season forecasts of return abundance, weights these forecasts to form a combined forecast of annual returns, and then subtracts the annual escapement objective and the cumulative catch to date in order to calculate the total allowable catch remaining in the season. This catch objective is then translated into weekly catch objectives using average run timing data. The management component then uses the number of gillnet vessels and historical data on weekly commercial fishery C/f to set the duration of the fishery opening to meet these weekly objectives.

Annual Escapement Objective

One of the goals of salmon fishery management is to achieve an annual number of spawners that will maximize sustainable yield (Minard and Meacham 1987, Sprout and Kadowaki 1987). In the simulation, I assume that the manager has perfect knowledge of the level of escapement (S_{opt}) that will maximize sustainable yield since the objective of my benefit-cost analysis is to determine the value of improved forecasts of sockeye returns, not the value of improved estimates of optimal escapement. The escapement target is derived from stock-recruitment analysis (Minard and Meacham 1987, Sprout and Kadowaki 1987). To calculate S_{opt}, I used the estimates of a_1, S_r, and σ^2_{v1} from the analysis of stock-recruitment above (Equation 2) and the approximate formula for S_{opt} from Hilborn (1985b),

Figure 15. Flow chart of Management Submodel and its relationship to the Sockeye Population Dynamics and Fishing Fleet Dynamics submodels.

MANAGEMENT SUBMODEL



(7) $$S_{opt} = S_r * a_p/a_1 *(0.5 - 0.07*a_p)$$

where

(8) $$a_p = a_1 + \sigma^2_{v,1} / 2$$

Given the parameter estimates from the stock-recruitment analysis above, a_p=1.23 and S_{opt}=795,000.

My estimate of optimum number of spawners is less than the published target of 900,000 spawners for Area 4 (Kadowaki et al. 1984), which is also based on stock-recruitment analysis (Sprout and Kadowaki 1987). The difference may be due to an inherent bias in my stock-recruitment methodology. Walters (1985) shows that the method I used to estimate the stock-recruitment parameters is biased downward due to the correlation between random deviations in S and subsequent levels of R. In the worst case, this bias may result in an underestimate of S_{opt} by 50%. However, my estimates of the stock-recruitment parameters and optimal escapement are internally consistent and are adequate for this simulation, which only requires some stock-recruit relation to drive the long-term population dynamics.

I set the target for escapement from the Area 4 fishery at 895,000 sockeye to allow for the optimal number of spawners and an Indian food fishery catch of 100,000 sockeye, approximately equal to the average harvest by the Indian food fishery, 1964-1983 (Kadowaki et al. 1984).

Pre-season Forecast of Annual Abundance of Returns

For all three management systems, I use the mean annual return of sockeye to Area 4 from 1966 to 1980 ($1.6X10^6$ fish) as the pre-season forecast for the first year of each simulation. In subsequent years of each simulation run, the pre-season forecast is updated by including the simulated annual abundance of returns from the previous year in the calculation of the mean.

I use mean abundance of returns as the pre-season forecast in the simulation because I found no significant relationship between the pre-season forecasts of returns (R. Kadowaki, DFO, Prince Rupert, personal communication) and the actual annual returns to Area 4 from 1967 to 1981 ($P(r=0)>0.9$).

For comparison with the other two forecasting methods below and for weighting the pre-season and in-season forecasts of abundance of returns, I calculated the PRESS statistic, the sum of squares of predicted residual errors (Henderson et al. 1987). This was calculated by dropping the i^{th} observation from the estimate of the mean, subtracting the i^{th} observation from the new mean to yield the residual error, and summing the squares of these residuals. For the pre-season forecast of annual abundance of returns, I found $PRESS=3.16X10^{12}$. The residual mean square ($RMS=2.87X10^{11}$) was calculated by dividing PRESS by the degrees of freedom, the number of observations minus one[1].

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[1] Through an error in calculation, the weighting factors for the forecasts in the simulations were calculated by dividing PRESS by the number of observations, not the degrees of freedom. This

I use the PRESS statistic rather than the residual sum of squares for two reasons. Henderson et al. (1987) note that (1) the residual sum of squares (RSS) underestimates the variance of a predicted value because the regression is based on that observation, and (2) the RSS decreases with the addition of variables that may not improve the precision of the prediction.

In-season Forecasts of Annual Abundance of Returns

Cumulative catch per effort data from the test fishery or from the commercial fishery may be used to calculate an in-season forecast of annual returns for TEST or COMM management, respectively. The forecast has two parts: (1) forecasting annual abundance from cumulative abundance to date (Walters and Buckingham 1975, Henderson et al. 1987), and (2) estimating cumulative abundance to date with C/f data from the test or commercial fisheries.

Annual abundance of returns in year j may be related to cumulative abundance in week t during the year as follows:

$$(9) \qquad N_j = b_{9t} * \sum_{i=t_1}^{t} NW_{i,j}$$

where b_{9t} is the reciprocal of the average cumulative proportion of the run returning between weeks t_1 and t, $NW_{i,j}$ is the weekly abundance of sockeye in Area 4 in week i of year j, and N_j is

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does not affect the relative weighting of the PRE, TEST, and COMM forecasts in the first three weeks of the simulations. However, in week 7-5 the variance of the COMM forecast is underestimated by 1% relative to that of the PRE and TEST forecasts, in week 8-1 by 3%, and in week 8-2 by 5%. The effect of this calculation error on the results should be minimal.

the annual abundance of sockeye in year j. The weekly coefficients (b_{9t}) can be estimated from historical data by regression constrained through the origin of annual abundance of returns on cumulative abundance to date for each week t. To make a forecast of abundance of annual returns, cumulative abundance of returns to date in the current year is multiplied by the weekly coefficient for that week (b_{9t}), calculated from the historical data. Cumulative abundance of returns to date is composed of weekly abundances of returns, which may be estimated from (1) weekly test fishery C/f and commercial catch data, or (2) weekly commercial fishery C/f data.

Test Fishery

Test fishery C/f is used to estimate weekly abundance of escapement from Area 4 and forecast annual abundance of returns during the season for TEST management. Since I found in the previous chapter that annual abundance of escapement and C/f in the test fishery were linearly related, I assume that the ratio of weekly escapement (E_w) to weekly catch per effort in the test fishery (C/f_w) is the same as the ratio of those annual variables, i.e. $E_w / (C/f_w) = E_y / (C/f_y)$. Weekly abundance of returns in the Area 4 fishery equals the weekly escapement estimated from the test fishery index plus the weekly catch

$$(10) \qquad NW_{i,j} = 589 * TC/f_{i,j} + C_{i,j}$$

where $TC/f_{i,j}$ is the sum of the daily C/f in the test fishery in week i of year j, 589 is the slope of the relationship between annual escapement and annual test fishery C/f calculated in the previous chapter, and $C_{i,j}$ is the commercial catch in Area 4 in week i of year j. Substituting the test fishery estimate of weekly abundance of returns into equation 9, then annual abundance of returns is related to test fishery C/f and commercial catch at any week t as

$$(11) \qquad N_j = b_{11t} * \left(589 * \sum_{i=1}^{t} TC/f_{i,j} + \sum_{i=1}^{t} C_{i,j} \right) + v_{11t}$$

where $b_{11t}=b_{9t}$ and v_{11t} is a normally distributed error term with variance σ^2_{v11t}.

I tested the significance of this relationship for each week t by regressing annual abundance of sockeye returns to Area 4 on cumulative weekly C/f in the test fishery and cumulative weekly catch in the commercial fishery, both accumulated from week 7-2 through week t. I started with week 7-2 because there were few years with commercial fishery openings prior to this week and the prediction sum of squares for the test fishery relationship was not improved by starting with an earlier week. Linear regressions ($y=a+bx$) for fishery weeks 7-4 through 8-4 were significant (all $P<0.002$) but with intercepts that were not significant (all $P(a=0)>0.05$), thus confirming the lack of intercept in equation 11. I then estimated the b_{11t} by constraining the regressions through the origin. I also calculated the residual mean square (RMS) errors of the predicted annual abundance of returns. The RMS error of the abundance forecast decreased throughout the season and by week

7-4, the test fishery became a better predictor of annual abundance than the pre-season forecast (Figure 16).

The estimate of b_{11t} from the linear regression is used in the model to simulate for TEST management an in-season forecast of annual return abundance in the current week (t) from simulated weekly test fishery C/f (TCF) and simulated weekly commercial catches (CW) accumulated to the previous week (t-1)

$$(12) \qquad INS_t = b_{11t-1} * (589 * \sum_{i=1}^{t-1} TCF_i + \sum_{i=1}^{t-1} CW_i)$$

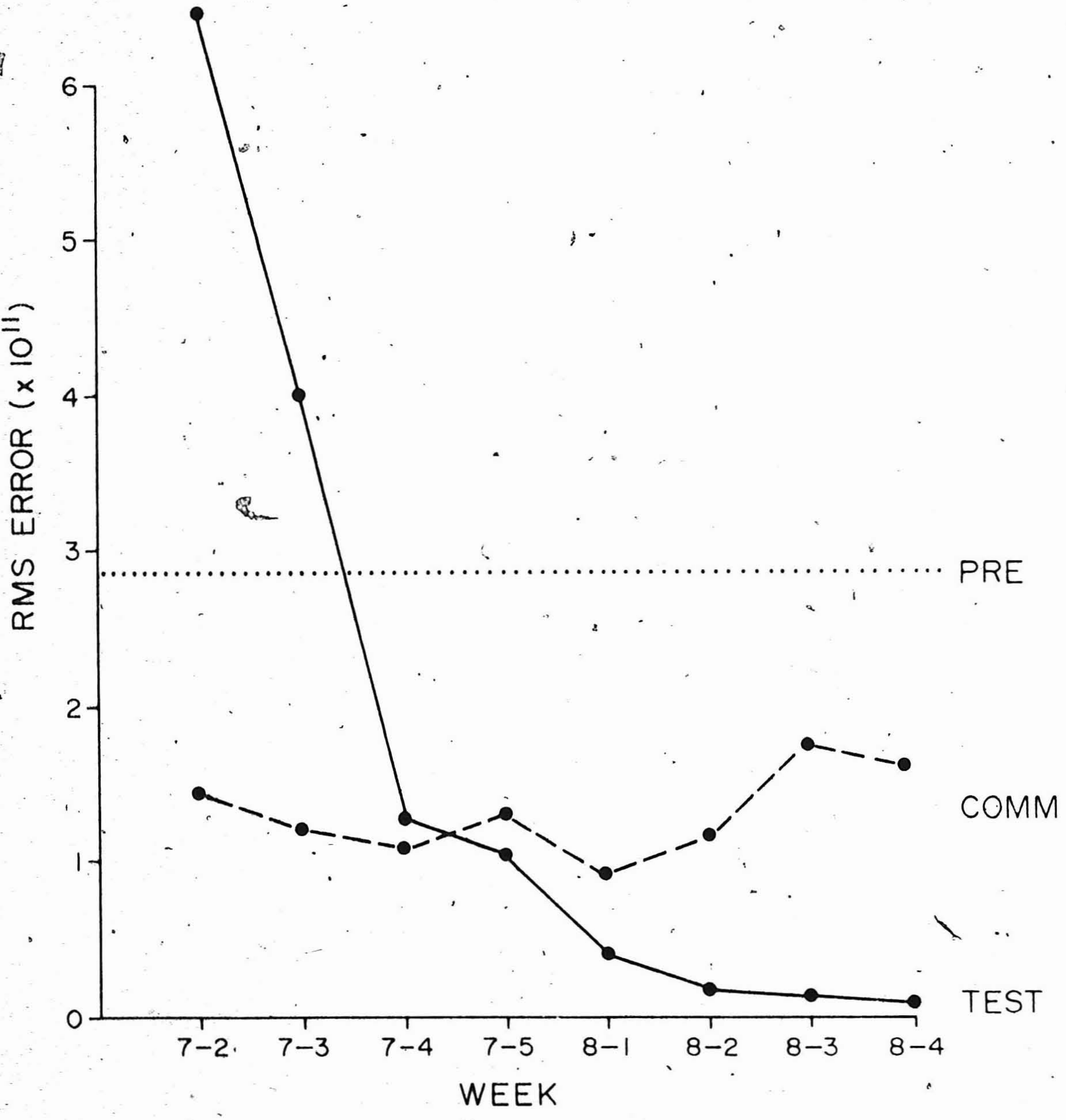
This is simply a return timing model for forecasting annual abundance of returns where cumulative test fishery C/f is an index of cumulative escapement to time t.

Commercial Fishery

Commercial fishery C/f is used to forecast annual abundance of returns during the season for COMM management. I found in the previous chapter that weekly commercial fishery C/f was nonlinearly related to weekly abundance of sockeye returns and that weekly harvest rate was nonlinearly related to nominal fishing effort. These findings imply that catchability is correlated with stock abundance or effort. In the model, q is related to nominal fishing effort through equation 6. Since effort is correlated with stock abundance, this results in apparent density-dependent q. For the calculation of return forecasts based on commercial fishery C/f, I assume that commercial fishery C/f is linearly related to stock abundance,

Figure 16. In-season time trends in prediction errors of pre-season forecast (PRE) and in-season forecasts based on commercial fishery C/f (COMM) and on test fishery C/f (TEST). Week 7-2 is the second week in July.

PREDICTION ERRORS OF FORECASTS



since the parameter estimates for the nonlinear relationships would not be available in the absence of weekly abundance of returns data from the test fishery. The estimate of weekly abundance (N) from the test fishery is required to estimate the parameters of the nonlinear functions for the functional response (C/f versus N) and the harvest rate (C/N versus f). However, in the sensitivity analysis of the model's results below, I found that the results were biased by this assumption of constant q. Therefore, I also ran the model with q corrected for changes in fishing effort.

Assuming a linear relationship between weekly abundance of returns and commercial C/f, then

$$(13) \qquad NW_{i,j} = b_{13} * GC/f_{i,j}$$

where b_{13} is the reciprocal of weekly q (from equation 2 in chapter 2, C=qfN) and $GC/f_{i,j}$ is the commercial fishery C/f in week i of year j. Substituting the commercial fishery estimate of weekly abundance of returns into equation 9, then annual abundance of returns is related to commercial fishery C/f at any week t as

$$(14) \qquad N_{t,j} = b_{14t} * \sum_{i=1}^{t} GC/f_{i,j} + v_{14t}$$

where $b_{14t}=b_{13}*b_{9t}$ and v_{14t} is a normally distributed error term with variance σ^2_{v14t}.

I tested the significance of this relationship by regressing annual abundance of sockeye returns to Area 4 on cumulative weekly C/f in the commercial gillnet fishery. Linear regressions ($y=a+bx$) for the first week (7-2) to the sixth week (8-2) were significant (All $P<0.03$) but with intercepts that were not significant (All $P(a=0)>0.15$), confirming the lack of intercept in equation 14. I then estimated the b_{14t} by constraining the regressions through the origin and for each week, I again calculated the residual mean square (RMS) error of the predicted annual abundance of returns. The RMS error of the abundance forecast remained relatively constant throughout the season. The commercial fishery was a consistently better predictor of annual abundance than the pre-season forecast and for the first 3 weeks, was a better predictor than the test fishery (Figure 16).

The estimates of b_{14t} from the linear regression are used in the model to simulate for COMM management an in-season forecast of annual return abundance from simulated weekly commercial gillnet fishery C/f (GCFW)

$$(15) \qquad INS_t = b_{14t-1} * \sum_{i=1}^{t-1} GCFW_i$$

or if the fishery was closed in week t, then

$$(16) \qquad INS_t = INS_{t-1}$$

These weekly forecasts assume that fishing effort each week in the model will be similar to that occurring historically.

Changes in weekly C/f are assumed to reflect only changes in stock abundance. In the model, q and thus C/f vary with nominal fishing effort which can bias the in-season forecast, if mean weekly effort in the model is different from that occurring historically. I standardized C/f ($GCFWS_t$) to correct for differences between weekly nominal fishing effort in the model and that in the corresponding week of the historical period on which the forecast parameters are based:

$$(17) \qquad GCFWS_t = GCFW_t * f_{hist,t}^{0.33} / f_{model,t}^{0.33}$$

where $GCFW_t$ is the simulated weekly commercial fishery C/f in the model, $f_{model,t}$ is simulated weekly nominal fishing effort in week t, $f_{hist,t}$ is the mean weekly fishing effort in the corresponding week of the historical period, and the exponent (0.33) is from equation 6. Results from simulations run with standardized commercial fishery C/f are presented in the Sensitivity Analysis below.

Weighting of Pre-season and In-season Forecasts

Pre-season and in-season forecasts of annual abundance of returns of sockeye to Area 4 are weighted to maximize the precision of the combined forecast of annual returns (Sprout and Kadowaki 1987). Following Walters and Buckingham (1974), I used weighted least squares to combine the forecasts in the model. This weighting method is less complicated than the Bayesian approach of Fried and Hilborn (1988). The variance of the mean of the independent observations $x_1, \ldots, x_n$ having unequal variances $\sigma^2_1, \ldots, \sigma^2_n$ is minimized by weighted least squares where the weights are the reciprocals of the variances of the individual observations, $1/\sigma^2_1, \ldots, 1/\sigma^2_n$ (Box et al. 1978). In each week t, the weighted forecast of abundance of returns (PN_t) is:

$$(18) \qquad PNW_t = \sum_{i=1}^{n} w_i * x_i \Big/ \sum_{i=1}^{n} w_i$$

where $w_i = 1/\sigma^2_i$ and the x_i are the i^{th} independent forecasts of abundance of returns (n=2 or n=3, as below).

For the two forecast case (COMM: pre-season and commercial fishery), equation 18 yields

$$\begin{aligned}(19) \qquad PNW_t &= \cancel{(w_1 * x_1} + w_1 * x_2) / (w_1 + w_2) \\ &= (1/\sigma^2_1 * x_1 + 1/\sigma^2_2 * x_2) / (1/\sigma^2_1 + 1/\sigma^2_2) \\ &= (\sigma^2_2 * x_1 + \sigma^2_1 * x_2) / (\sigma^2_1 + \sigma^2_2)\end{aligned}$$

where x_1 is the pre-season forecast, x_2 is the in-season forecast based on commercial fishery C/f (Equation 15), and σ^2_1 and σ^2_2 are their respective prediction error variances. These variances are calculated from the PRESS (Table 4).

For the three forecast case (TEST: pre-season, commercial fishery, and test fishery):

$$\begin{aligned}(20) \qquad PNW_t &= (w_1 * x_1 + w_2 * x_2 + w_3 * x_3) / (w_1 + w_2 + w_3) \\ &= (1/\sigma^2_1 * x_1 + 1/\sigma^2_2 * x_2 + 1/\sigma^2_3 * x_3) / \\ &\quad (1/\sigma^2_1 + 1/\sigma^2_2 + 1/\sigma^2_3) \\ &= (\sigma^2_2 * \sigma^2_3 * x_1 + \sigma^2_1 * \sigma^2_3 * x_2 + \sigma^2_1 * \sigma^2_2 * x_3) / \\ &\quad (\sigma^2_2 * \sigma^2_3 + \sigma^2_1 * \sigma^2_3 + \sigma^2_1 * \sigma^2_2)\end{aligned}$$

Table 4. Estimates of parameters and weighting factors for the pre-season forecast (PRE), the in-season forecast based on test fishery C/f and commercial catch (TEST, Equation 11), and the in-season forecast based on commercial fishery C/f (COMM, Equation 14). Weighting factor is PRESS divided by number of observations. Mean nominal fishing effort (f_{hist}) for 1966-72, 1974, and 1977-80 is calculated for standardizing commercial fishery C/f in the model. Weekly test and commercial fishery C/f are accumulated from week 7-2.

	PRE	TEST		COMM		
Week	RMS	b_{11t}	RMS	b_{14t}	RMS	f_{hist}
7-2	2.63×10^{11}	9.96	5.86×10^{11}	22100	1.34×10^{11}	890
7-3	2.63×10^{11}	3.43	3.63×10^{11}	9860	1.13×10^{11}	1670
7-4	2.63×10^{11}	2.04	1.16×10^{11}	6140	1.02×10^{11}	1739
7-5	2.63×10^{11}	1.46	9.94×10^{10}	4670	1.18×10^{11}	1742
8-1	2.63×10^{11}	1.23	3.91×10^{10}	3990	8.16×10^{10}	1455
8-2	2.63×10^{11}	1.16	1.50×10^{10}	3560	1.05×10^{11}	949
8-3	2.63×10^{11}	1.14	1.44×10^{10}	3180	1.41×10^{11}	
8-4	2.63×10^{11}	1.11	7.15×10^{09}	3010	1.21×10^{11}	

where x_1 is the pre-season forecast, x_2 is the in-season forecast based on commercial fishery C/f (Equation 15), x_3 is the in-season forecast based on test fishery C/f and commercial catch (Equation 12), and σ^2_1, σ^2_2, and σ^2_3 are their respective prediction error variances (Table 4).

Total Allowable Catch Remaining in Season

The basic objectives of management in the simulation are to allow the desired number of total spawners (S_{opt}) to escape the fishery and to apportion the allowable catch in excess of these escapement requirements over all weekly segments of the run. The latter objective is consistent with the weekly escapement targets set by managers of the Area 4 sockeye fishery (Sprout and Kadowaki 1987) and with the objective of orderly harvest. At any time t during the simulated season, the total allowable catch in the remainder of the season (TAC_t) is simply the difference between the weighted forecast of annual returns (PN_t) and the larger of the annual escapement target (S_{opt}) or the cumulative escapement to date, less the cumulative catch to date:

$$(21) \qquad TAC_t = PN_t - MAX(S_{opt}, \sum_{i=1}^{t-1} EW_i) - \sum_{i=1}^{t-1} CW_i$$

Cumulative escapement to date is set to zero for PRE and COMM management since there is no estimate of cumulative escapement during the season.

The total allowable catch to come is divided across the remaining weeks in proportion to their weekly abundance of returns, based on average historical run timing data. The weekly catch objective in week t ($TACW_t$) is thus:

$$(22) \qquad TACW_t = TAC_t * PW_t / \sum_{i=t}^{nro} PW_i$$

where nro is the number of remaining openings. For TEST management, the PW_i (Table 5) are calculated from the b_{11t}, the reciprocals of the cumulative proportions of the annual abundance of returns in week t (Equation 11):

$$(23) \qquad PW_t = 1/b_{11t} - 1/b_{11t-1}$$

The proportion of the run returning in week t is estimated by subtracting the cumulative proportion of the run returning in week t-1 (b_{11t-1}) from the cumulative proportion of the run returning in week t (b_{11t}). For PRE and COMM management, the PW_i are calculated from the b_{14t}, which are proportional to the reciprocals of the cumulative proportions of the annual abundance of returns in week t (Equation 14):

$$(24) \qquad PW_i = 1/b_{14t} - 1/b_{14t-1}$$

Duration of Fishery Opening

Given this weekly catch objective, the control variable for the fishery is the duration of the fishery opening. Length of the opening is determined by the number of fishing vessels and their predicted catch per effort. The actual abundance of

Table 5. Weights (PW_t) for allocating total allowable catch across the remaining weeks in the fishing season. For TEST management, PW_t is an estimate of the proportion of the run returning in week t (p_t) and for PRE and COMM management, it is $(1/q)*p_t$, an index of p_t (See equations 9, 13 and 14).

Week	PRE/COMM (x1000)	TEST
7-2	0.045	0.10
7-3	0.056	0.19
7-4	0.061	0.20
7-5	0.051	0.19
8-1	0.036	0.13
8-2	0.030	0.05
8-3	0.034	0.02
8-4	0.018	0.02

fishing vessels (GNW_t), simulated in the model by equation 5, is known prior to setting the length of the opening. In the field situation in Area 4, it is estimated by aerial overflight immediately after the fishery opening. This number is used in conjunction with a simulated prediction of weekly C/f ($PGCF_t$) to estimate the duration of the opening, which is the weekly catch objective ($TACW_t$) divided by the predicted catch by the gillnet fleet per day open:

(25) $$DAYS_t = TACW_t / (PGCF_t * GNW_t)$$

For the first week of the fishery, I set a minimum opening length of 2 d and maximum of 3 d, the range of actual opening lengths for this week from 1966-80. For the remaining weeks of the fishery, duration of the opening is set with equation 25. However, the model would close the fishery for weeks where the calculated duration was less than 0.25 d.

Predicted Gillnet C/f

If the proportion of the run returning in week t (p_t) and weekly q are constant over years, then weekly C/f (C/f_t) could be predicted from estimates of annual abundance (N):

(26) $$\begin{aligned} C/f_t &= q * N_w \\ &= q * (p_t * N) \\ &= a_{26t} * N \end{aligned}$$

where N_w is weekly abundance and a_{26t} is estimated from regressions of historical data. I use the historical mean weekly gillnet C/f (Table 6) as the predictor of C/f because I did not find consistently significant relationships between commercial fishery C/f in week t and annual abundance of returns.

Test Fishery C/f

Simulated weekly C/f in the test fishery is calculated from simulated weekly escapement:

$$(27) \qquad TC/f_t = b_{27} * EW_t * e^{v27}$$

where TC/f_t is weekly test fishery C/f and EW_t is weekly escapement past Area 4. The coefficient, b_{27}, and its variance, σ^2_{v27}, were estimated from the mean and variance of $\log_e((TC/f_y)/(E_y))$, where TC/f_y and E_y are the annual variables for 1966 to 1980. I found $b_{27}=1.69X10^{-3}$ and $\sigma^2_{v27}=0.027$.

Weekly Fishery Operation

The model simulates the true catch,

$$(28) \qquad CW_t = MW_t * NW_t$$

calculates the weekly C/f in the commercial fishery,

$$(29) \qquad GCFW_t = CW_t / (GNW_t * DAYS_t)$$

updates the true weekly escapement,

$$(30) \qquad EW_t = NW_t - CW_t$$

and accumulates the annual abundance of escapement (E)

$$(31) \qquad E = E + EW_t.$$

Table 6. Estimates of parameters, correlation coefficients, and their significance for relationships between weekly commercial gillnet C/f in each week and annual abundance of ~~returns~~ (Equation 26), 1966-1980, and mean weekly gillnet C/f, 1966-1980.

Week	$a_{26t} X10^{-3}$	r	P(r=0)	Mean C/f
7-2	4.92	0.76	0.004	67
7-3	6.26	0.47	0.12	88
7-4	6.92	0.39	0.21	97
7-5	6.09	0.09	0.80	88
8-1	4.93	0.71	0.02	70
8-2	3.41	0.26	0.47	47
8-3	1.30	0.39	0.34	17
8-4	0.45	0.17	0.69	6

and the annual catch

$$(32) \qquad C = C + CW_t$$

In the model, the Indian food fish harvest is 100,000 sockeye or one-half the annual escapement from Area 4, whichever is less, and this value is subtracted from the escapement to yield the annual abundance of spawners.

Economic Submodel

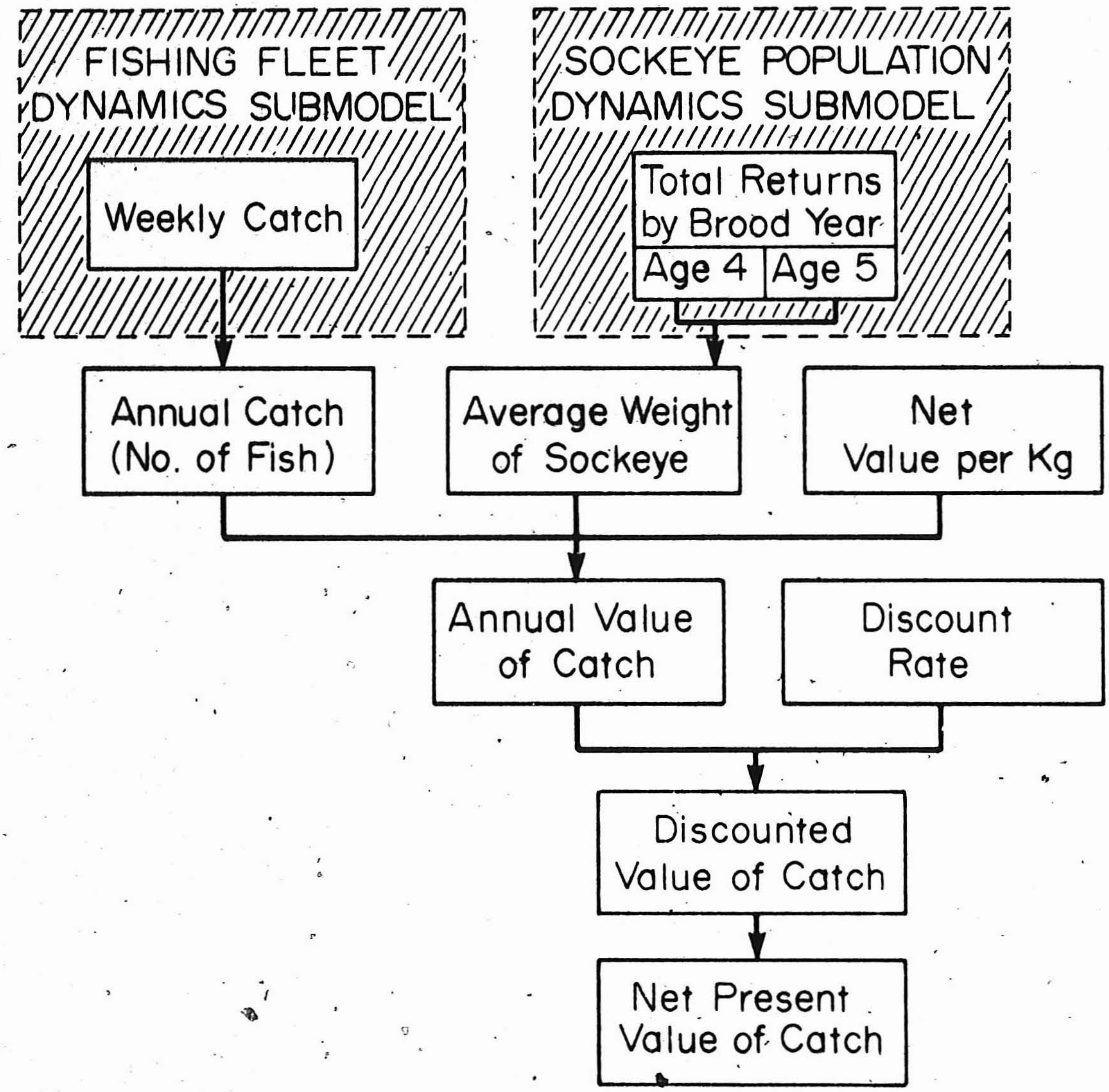
The economic evaluation component calculates the mean value of the annual catch and the mean net present value of the catch over 100 simulations, each of 50 yr duration (Figure 17). Mean annual value of the catch is an appropriate indicator of total benefit because benefits and costs are incurred simultaneously over time; there is no initial capital expense that must be offset by discounted benefits from later years. To simplify discussion, I only present results based on mean annual value of the catch. Conclusions based on net present values are similar and these values are tabulated in Appendix E. To calculate the benefit of test fishery information, I subtract the mean catch value of the next best alternative from that of the test fishery. This benefit is then compared with the annual cost of including the test fishery in the management program.

Annual Benefits

Annual net value of the sockeye catch (B$) is estimated as the difference between the wholesale value of the catch and the

Figure 17. Flow chart of Economic Submodel and its relationship to the Fishing Fleet Dynamics and Sockeye Population Dynamics submodels.

ECONOMIC SUBMODEL



costs of harvesting and processing. Abundance of catch is converted to weight of catch and then multiplied by the marginal value of sockeye per kilogram (W$).

(33) $$B\$ = C * AveWt * W\$$$

The average weight of sockeye in the catch (AveWt) is the mean of weights of age 4 and 5 sockeye, weighted by their relative abundances:

(34) $$AveWt = (AveWt_4 * R_{y-4} + AveWt_5 * R_{y-5}) / (R_{y-4} + R_{y-5})$$

where $AveWt_4$ and $AveWt_5$ are the average weights of age 4 and 5 sockeye, respectively, and R_{y-4} and R_{y-5} are the abundances of returns of age 4 and age 5 sockeye, respectively. I calculated the mean weight at age by first calculating the mean post-orbital to hypural lengths of age 4 and 5 yr old male and female sockeye caught in the Area 4 commercial gillnet fishery, 1966-72 (Kadowaki, unpublished MS). To calculate the mean length at age for both sexes combined, I used the mean sex composition of the Area 4 catch during this period to weight the mean length at age by sex. I then used a weight-length regression (Bilton 1985) to convert mean length at age to mean weight at age and found the mean whole weight of age 4 sockeye to be 2.3 kg and that of age 5 sockeye to be 3.3 kg.

I used the difference between the wholesale value of canned sockeye caught in net fisheries in 1985 ($6.91 per kg) and the marginal cost of harvesting and processing (24%) to calculate a marginal value of $5.25 per kg (W$), the value of catching one more kg of sockeye in a gillnet fishery (R. Mylchreest, DFO, Vancouver, personal communication). This value will result in overestimation of the total benefit of the fishery since fixed costs (e.g. opportunity cost of capital investment) are not subtracted. However, this value is appropriate for comparing the cases with and without test fishery information because both cases include the bias equally. Wholesale value of canned sockeye is used since most of the gillnet caught sockeye from Area 4 are canned and exported.

Annual Costs

The cost of operating the test fishery consists of costs associated with (1) installation and removal each year of the temporary wharf at the test fishery site on the Skeena River, (2) collecting biological information on the sampled fish, (3) maintenance and replacement of the test fishery net, (4) analysis of the data, and (5) supervision of the project by DFO personnel.

The cost of operating the test fishery is partly recovered from the resource; the test fishery charter is paid in fish. Commercial fishermen bid for a contract to operate the test fishery, which includes wharf installation and removal, net maintenance, and collection of biological information. The contract stipulates the duration of the test fishery charter and fishermen indicate the minimum guaranteed biomass of fish per day required for them to operate the test fishery. If the catch is less than this amount, DFO makes up the difference. Exact information on charter cost is confidential and the value of the contract fluctuates from year to year with the price of fish but the contract value is approximately $100,000 per year (D. Peacock, DFO, Prince Rupert, personal communication).

Analysis of the data and supervision of the contract require approximately 2 weeks per year of technician time and 1 week per year of biologist time (D. Peacock, personal communication). Assuming daily rates in 1985, including benefits and overhead, of $150 per day for a technician and $250 per day for a biologist, the annual cost of supervisory personnel is $2,750. These are approximate market rates based on values in proposals from consulting firms. A budget of $10,000 per year is allocated for net replacement and incidental costs of supervision. Annual cost to the DFO budget is therefore approximately $13,000.

Replacement of the wharf is expected to cost approximately $20,000 and occur every 10 yr (D. Peacock, personal communication). To compare with other annual costs, I calculated the levelized annual cost of wharf replacement. This is the net present cost of wharf purchase in year 1 and replacement at years 11, 21, 31 and 41 multiplied by the capital charge rate (CCR):

$$(35) \qquad CCR = r / (1 - (1+r)^{-n})$$

where r is the discount rate (0.1) and n is the time horizon (50 yr). The levelized annual cost of wharf replacement is $3,141.

Average annual cost is thus a maximum of \$116,000 per year and is likely much less. This value is a maximum because the value of the test fishery contract includes benefits. These benefits are the difference between the value of all fish caught by the test fishery and the costs of harvest. The only true costs of operating the test fishery are the additional costs of installing and removing the wharf each year, processing the biological information, and using standardized procedures to harvest the fish. Therefore, the annual cost is likely much less than the contract bid price. However, this estimate provides an upper bound to the cost and the overestimation does not affect the conclusions of the benefit-cost analysis.

Net Present Value

Annual benefit ($B\$_j$) and annual cost ($C\$_j$) for year j are discounted to yield net present values of benefit (NPB\$) and cost (NPC\$):

$$(36) \qquad NPB\$ = \sum_{j=1}^{50} B\$_j/(1+r)^j$$

$$(37) \qquad NPC\$ = \sum_{j=1}^{50} C\$_j/(1+r)^j$$

I use a discount rate (r) of 0.1 or 10% per year (Treasury Board 1976) and a time horizon in the simulation of 50 yr. The 50 yr simulation encompasses 10 complete cycles of sockeye reproduction and at this discount rate, the 50th year contributes less than 0.01% to the net present value. An annual cost of $116,000 per year discounted at 10% per year over 50 yr yields a net present cost of $1,260,000.

Results

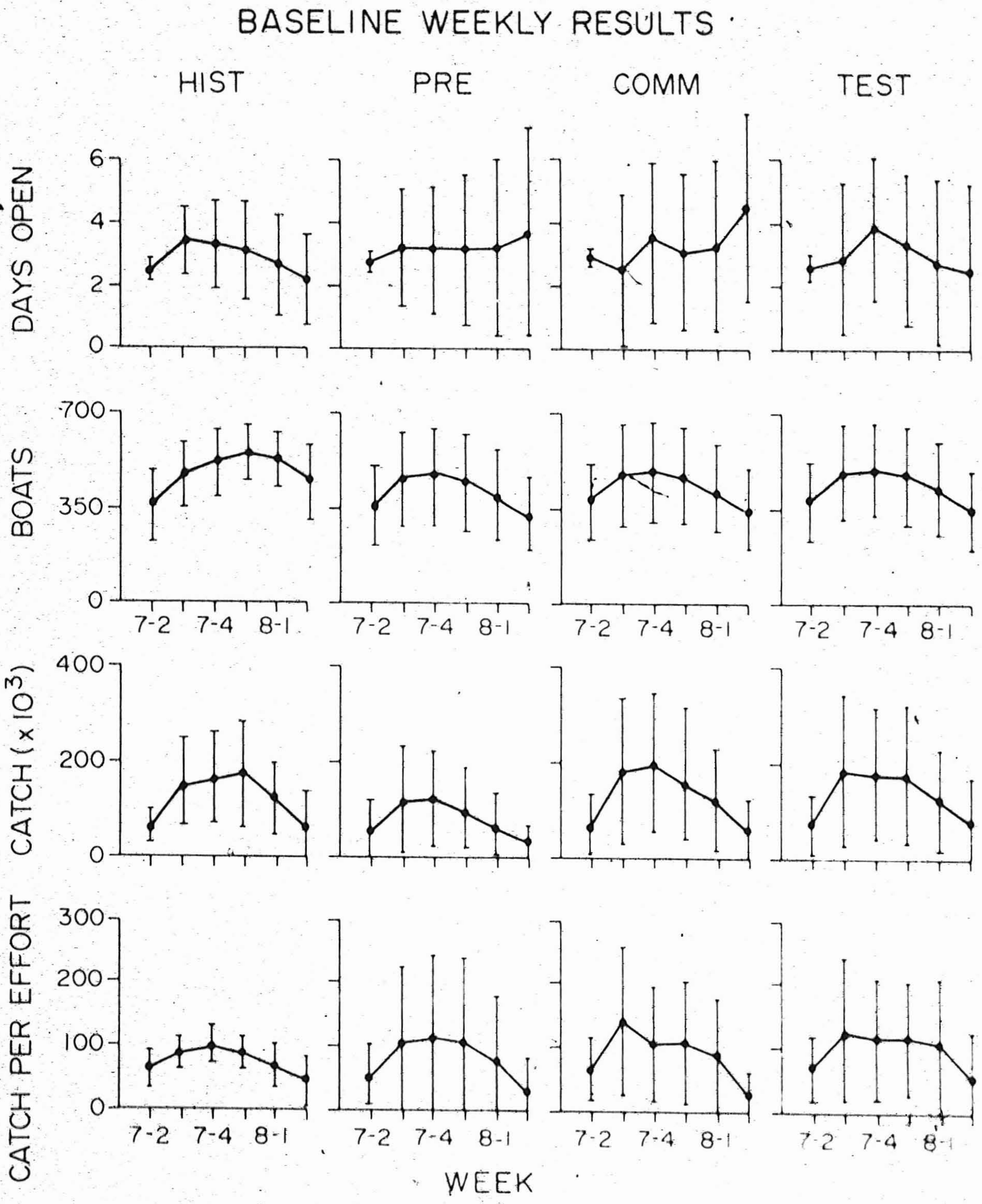
Baseline Simulation

Weekly results from the three simulations (one for each method of forecasting returns in-season) show patterns similar to historical ones (Figure 18). Differences from the historical data occur because the simplified relationships in the model do not completely capture the dynamics of the sockeye stock, the fishery, or its management. The model will, regardless of these differences, be internally consistent for comparing the performance of the fishery managed with and without test fishery information.

Weekly Results

Number of days open each week in the simulations are less than the historical data and the variance in number of days open (across the 100 separate simulations) is greater than the historical data for all weeks except the first (Figure 18). In the first week, the simulations were constrained to open for only 2 to 3 days. The higher variance in simulated number of days open is due to the higher variance in simulated annual abundance of returns (Figure 19b); the standard deviation of

Figure 18. Baseline Weekly Results. Weekly results of 100 simulations of 50 yr duration with baseline conditions for the three management scenarios, PRE, COMM, and TEST, compared with historical data for Area 4 (HIST). Means and standard deviations (SD) of duration of fishery (Days Open) and number of gillnet vessels (Boats) are calculated with values from all weeks; those of catch and catch per effort (catch per boat-day) are calculated only with values from weeks in which the fishery was open. Error bars indicate plus and minus one SD. Fishery week 7-2 is the second week in July.


BASELINE WEEKLY RESULTS
HIST
PRE
COMM
TEST
DAYS OPEN
6
4
2
0
BOATS
700
350
0
CATCH (x 10³)
400
200
0
CATCH PER EFFORT
300
200
100
0
7-2
7-4
8-1
WEEK

annual abundance of returns in the simulations is 32 - 38% greater than the historical data.

In all scenarios, the weekly abundance of gillnet vessels in the model is similar to the historical data for the first three weeks of the fishery but is underestimated in later weeks. This is due in part to a residual time trend in weekly effort not captured in the numerical response function (Equation 5). In the previous chapter in the analysis of the effect of sockeye abundance on effort, I found that the residuals from the linear model increased with time during the season but that the time trend was not significant. In the simulation model, this time trend results in slight overestimation of effort relative to historical effort early in the season and underestimation of effort late in the season. The degree of underestimation later in the season is exacerbated by the way in which the results are presented. In the historical data, the mean is based on values from weeks in which the fisheries were open. In the simulations, it is based on values from all weeks, including those in which there were no fisheries. In the model, vessels respond linearly to weekly abundance of returns so this biases the mean downward since "no fishery" implies low stock abundance and thus lower number of vessels.

Mean catches during weekly fisheries in the COMM and TEST scenarios are similar to the historical data but those of the PRE scenario are less than the historical data. This is due to lower mean weekly abundance of sockeye in the PRE scenario.

Lack of in-season feedback to the stock forecast and fishery management led to overharvest; mean annual returns of sockeye in the PRE scenario is 26% less than the historical data. Unlike the other two management schemes, even when returns are less than the pre-season forecast, PRE management keeps the fishery open in the hopeless pursuit of the catch objective. In this situation, these fisheries lower the mean catch in the later weeks.

Differences in mean weekly C/f between the simulations and the historical data result from differences in weekly stock abundance and from differences in the catchability coefficient. For example in week 7-3, mean C/f in the COMM scenario is 64% greater than mean C/f in the same week of the historical period. The mean weekly abundance of sockeye in weeks when the fishery was open in this scenario is 21% greater than the historical data. Also, the mean catchability coefficient, q, in the COMM scenario is 26% greater than the historical data. This increase in q results from a distribution of nominal fishing effort highly skewed toward low values and from the nonlinear increase in q with decreasing effort implied by the harvest rate function in the model.

Annual Results

The simplified functions and management schemes in the model do not completely capture the dynamics of the fishery but the effect of this bias on the calculation of the incremental benefit of improved forecasts of annual returns should be minimal. All three management scenarios produce lower mean abundance and higher variance of annual returns, catch, and escapement than the historical data, although the TEST scenario produces values closest to the historical data (Figure 19). Lower mean catch will bias downward the *total* benefits of improved in-season forecasts which may reduce the absolute but necessarily the proportional *difference* in benefits between the management scenarios. However, any potential bias in the incremental benefit of improved information will be minimized because only the management system is changed between scenarios; all other factors are held constant in the model.

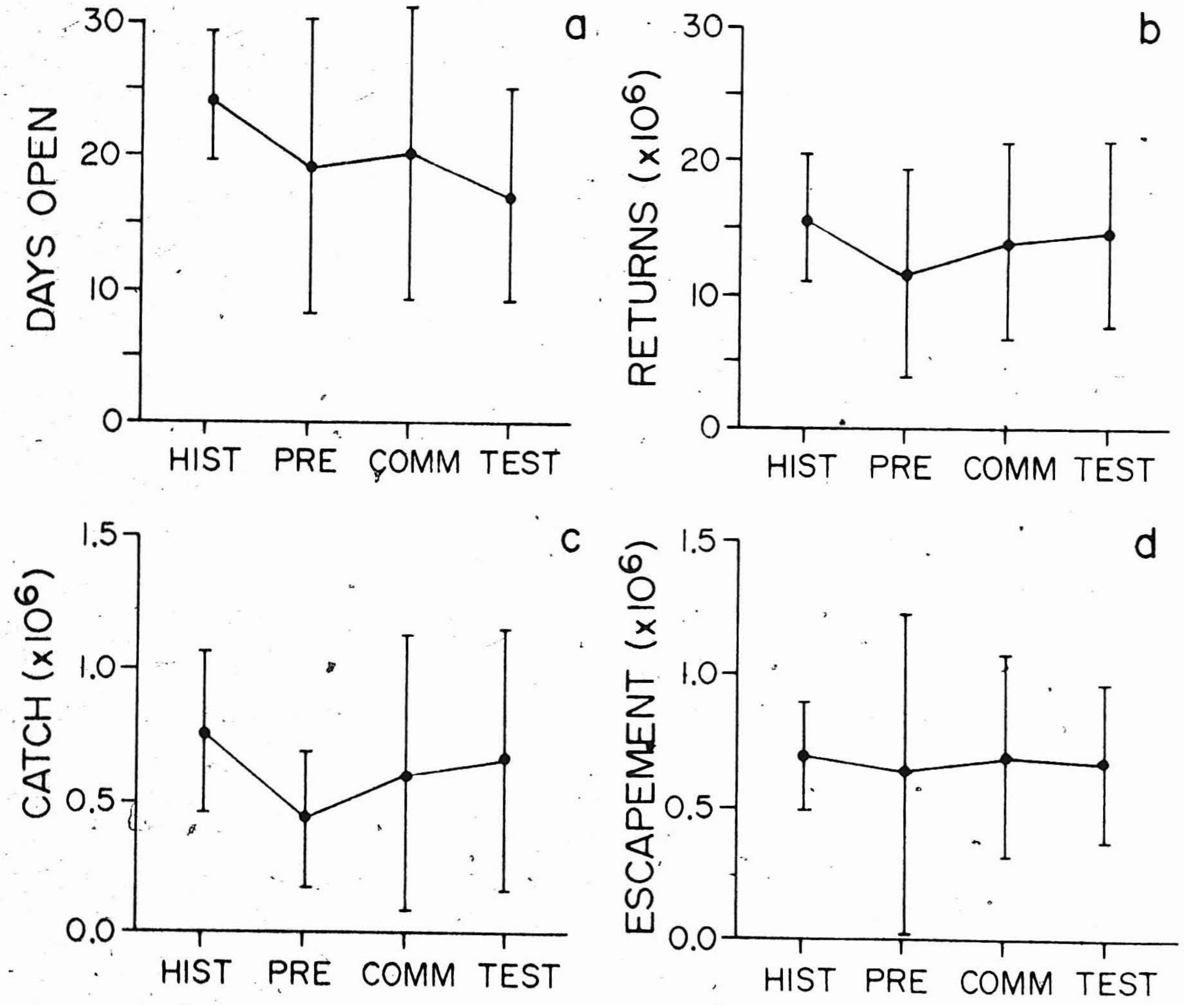
In all scenarios, the mean escapement is less than the escapement target of 795,000 sockeye. This is due to the occurrence in the simulations of returns less than the escapement objective.

All three scenarios have 5 to 7 fewer days open than in the historical period. This is due to the limitation of the fishery in the simulation to weeks 7-2 through 8-2. Historically, the fishery was open on average for 6.3 d in weeks before and after this period. The mean annual number of days open historically in this period was 17.2 d, close to the 17 to 20 d in the simulations.

Improved forecasts of annual abundance of returns result in smaller deviations from the annual escapement objective which lower the variance of annual abundance of returns (Figure 19). The standard deviation of escapement abundance for PRE

Figure 19. Baseline Annual Results. Annual results from 100 simulations of 50 yr duration for the three management scenarios, PRE, COMM, and TEST, compared with historical data (HIST). Due to fishery strikes in 1973 and 1975, these years were omitted from statistics on annual catch, escapement, and number of days open. Means and standard deviations (SD) are calculated for number of days open, annual abundance of returns, catch, and escapement. Number of days open is for weeks 6-1 through 8-4 only, the period when sockeye are harvested by the commercial net fishery in Area 4.

BASELINE
ANNUAL RESULTS



management is 59% greater than that for COMM management which is 30% greater than that for TEST management. Deviations from the escapement objective contribute to the variance of abundance of returns. The standard deviation of abundance of returns for PRE management is 5% greater than that for COMM management which is 4% greater than that for TEST management.

Improved forecasts also produce higher mean abundance of returns and higher value of the annual catch. Mean catch for TEST management is 7% (45,000 sockeye) greater than that for COMM management which is 41% (178,000 sockeye) greater than that for PRE management. The mean value of the catch for TEST management is $660,000 greater than that of the next best alternative, COMM management, which is $2,620,000 greater than that of PRE management (Figure 20).

Sensitivity Analysis

Standardized Commercial C/f

I also ran the baseline simulation with C/f in the commercial fishery standardized for the effect of effort on q. Through the harvest rate function (Equation 6), increases in fishing effort decrease q which reduces C/f and thus biases downward the in-season forecast based on commercial fishery C/f data. Standardizing the catchability coefficient for changes in nominal fishing effort (Equation 17) increases the mean number of gillnet vessels, increases C/f during weekly fisheries, and increases mean weekly catch from baseline for the COMM and TEST management is 59% greater than that for COMM management which is 30% greater than that for TEST management. Deviations from the escapement objective contribute to the variance of abundance of returns. The standard deviation of abundance of returns for PRE management is 5% greater than that for COMM management which is 4% greater than that for TEST management.

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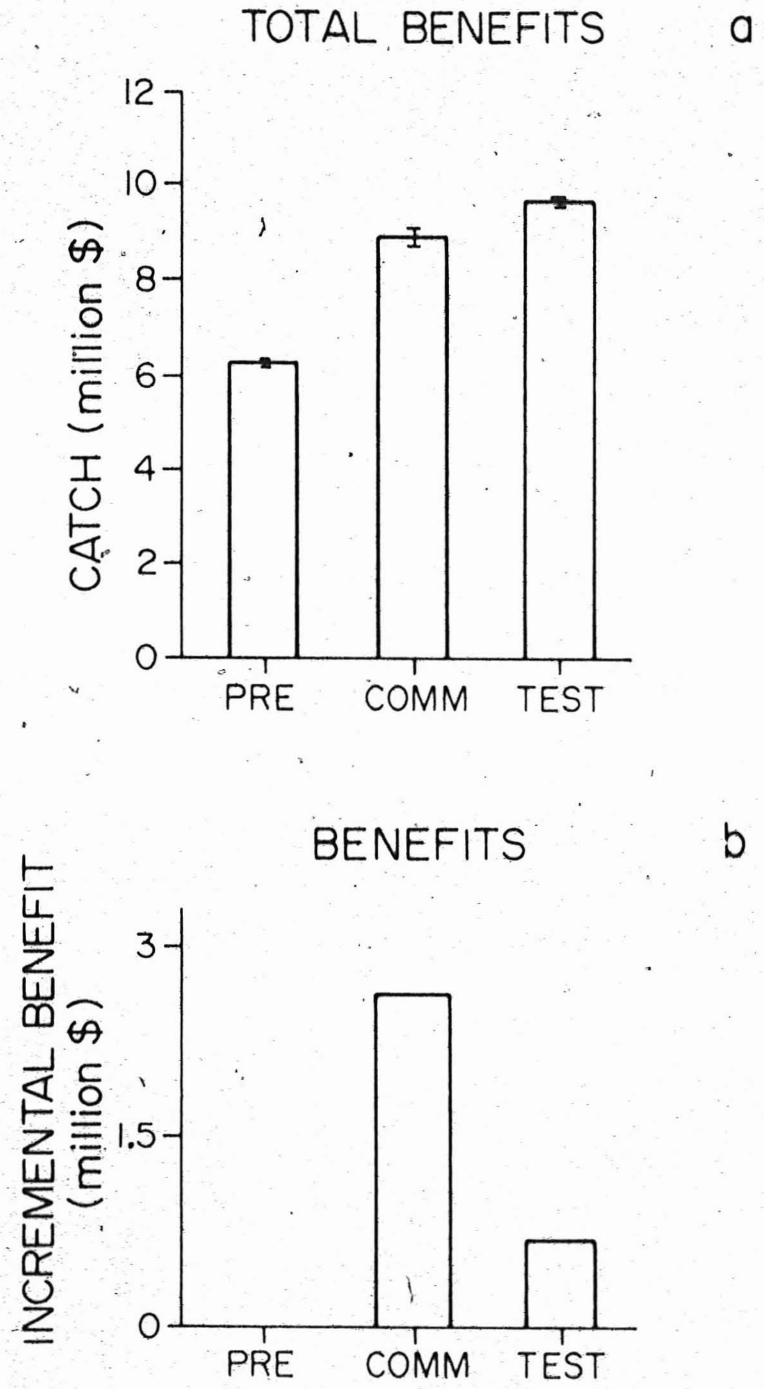
Figure 20. Baseline Annual Benefits.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

BASELINE


TOTAL BENEFITS
a
CATCH (million $)
12
10
8
6
4
2
0
PRE
COMM
TEST
BENEFITS
b
INCREMENTAL BENEFIT (million $)
3
1.5
0
PRE
COMM
TEST

scenarios (Figure 21). These slight improvements are due to reduced bias in the in-season forecast based on commercial fishery C/f. When returns are low, the management submodel decreases nominal fishing effort (number of boats X duration of opening) to take the weekly catch objective. However, the catchability coefficient increases with this decrease in effort and weekly C/f is biased upward relative to the historical values on which the in-season forecast is based. This results in an upward bias in the forecast of returns and overharvest of low returns. High returns are underharvested due to q decreasing with the higher level of fishing effort required to harvest the weekly catch. By eliminating the dependence of q on effort in the forecast, the forecasts are less biased, deviations from the escapement objective are reduced, and mean annual returns increase over baseline. This results in increased number of vessels, since vessels respond to stock abundance. Weekly catch and C/f also increase, due to the increase in mean stock abundance and to the reduction in overharvest of low returns and underharvest of high returns, which lowers mean C/f and mean catch.

Standardization of commercial C/f in the in-season forecast further reduces annual deviations from the escapement objective and increases mean annual returns and catch (Figure 22). However, standardization implies knowledge of stock abundance which would not be available to COMM management in the absence of test fishery data. In the COMM and TEST scenarios, the standard deviations of the annual escapement drop 10% and 20%,

Figure 21. Weekly Results (Standardized Commercial C/f). Weekly results of simulations for the three management scenarios, PRE, COMM, and TEST, with standardization of commercial fishery C/f for effect of nominal fishing effort on q (See equation 17 and In-season Forecasts of Annual Abundance of Returns for details). Means and standard deviations (SD) of duration of fishery (Days Open) and number of gillnet vessels (Boats) are calculated with values from all weeks; those of catch and catch per effort (catch per boat-day) are calculated only with values from weeks in which the fishery was open. Error bars indicate plus and minus one SD. Fishery week 7-2 is the second week in July.

STANDARDIZED COMMERCIAL
CATCH PER EFFORT
WEEKLY RESULTS

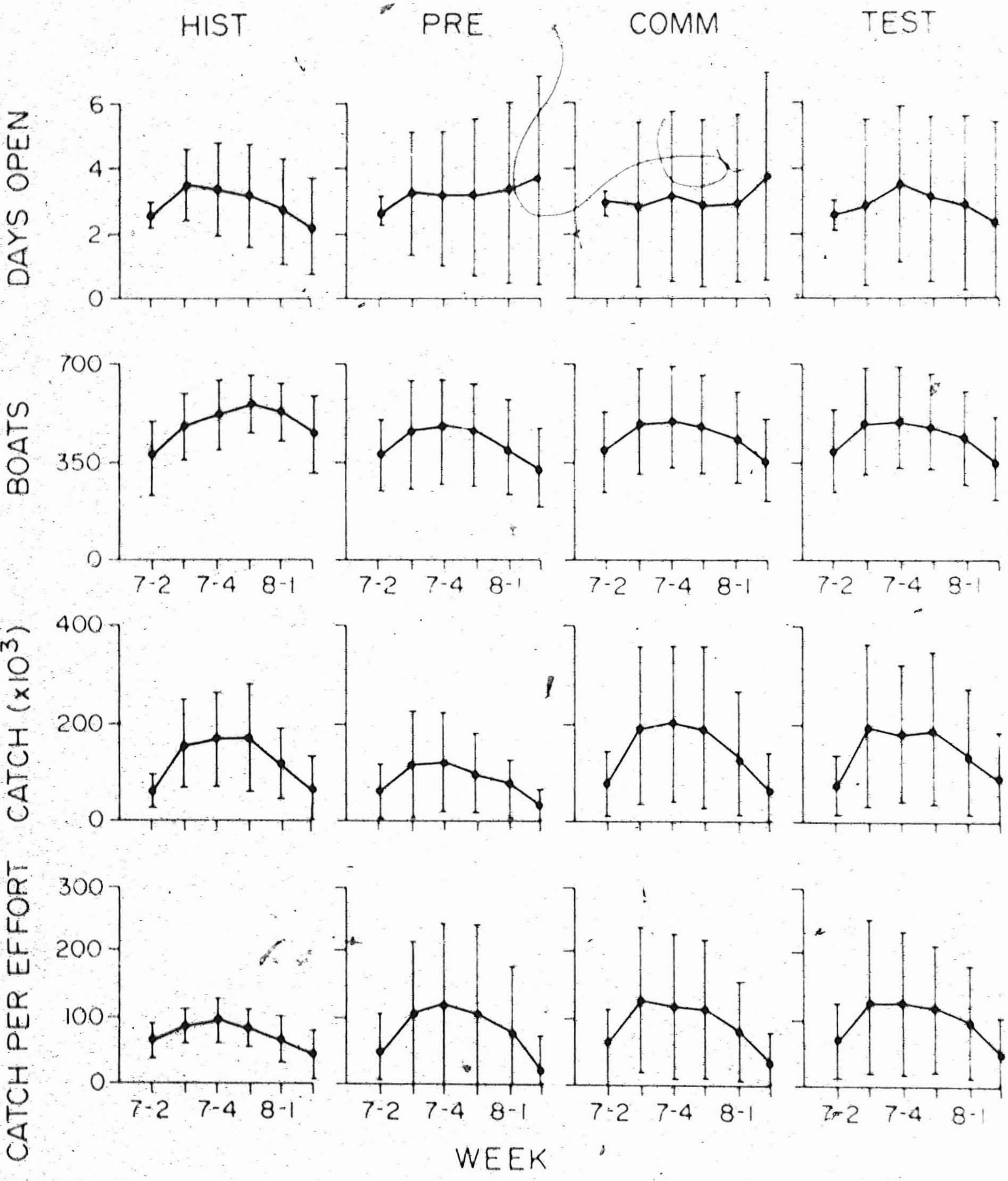
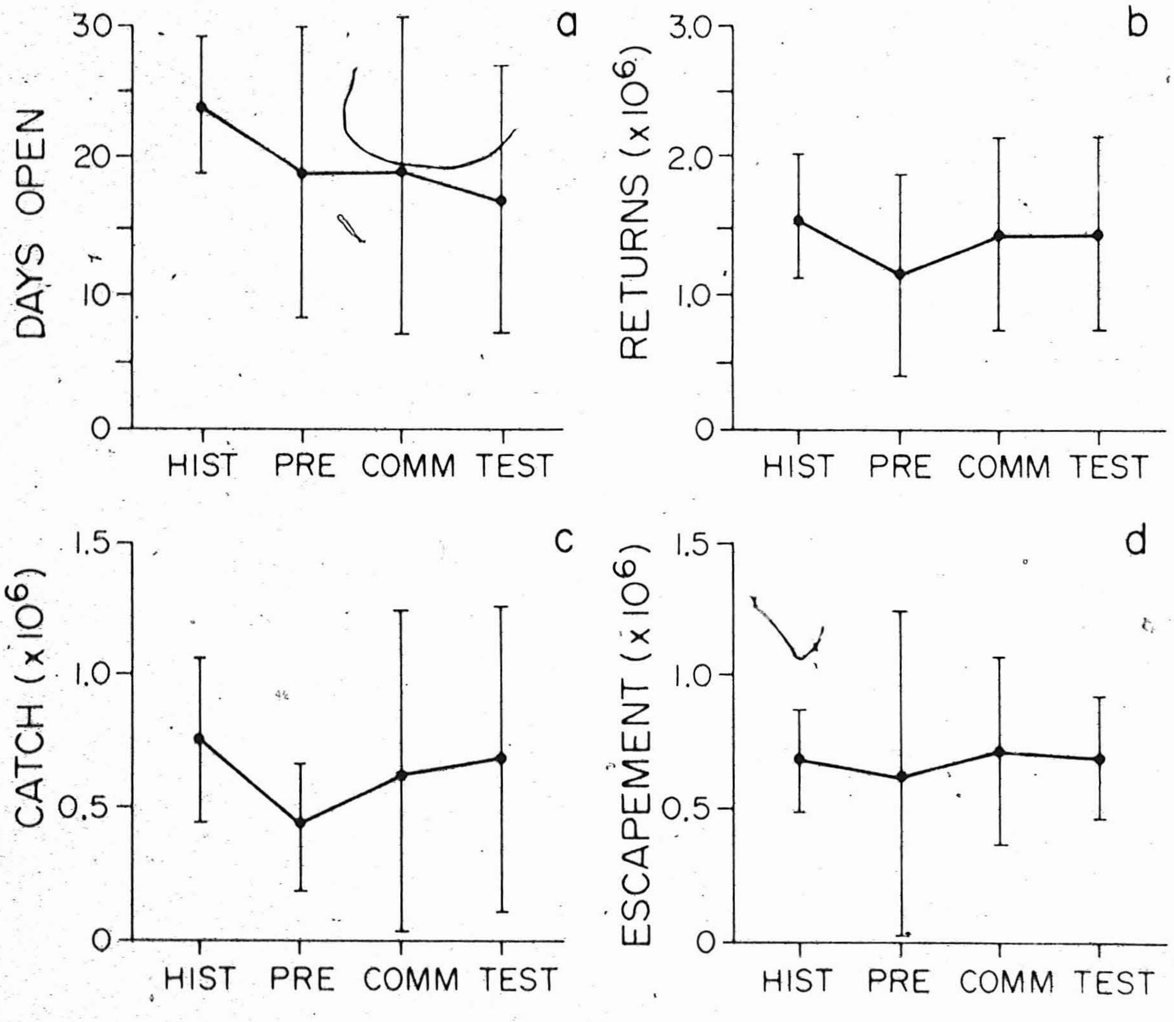


Figure 22. Annual Results (Standardized Commercial C/f). Annual results of simulations for the three management scenarios, PRE, COMM, and TEST, compared with historical data (HIST). Commercial fishery C/f is standardized for the effect of nominal fishing effort on q. Means and standard deviations (SD) are calculated for number of days open, annual abundance of returns, catch, and escapement. Number of days open is for weeks 6-1 through 8-4 only.

STANDARDIZED COMMERCIAL CATCH PER EFFORT ANNUAL RESULTS



respectively, from baseline. Mean annual returns and mean annual catch increase 3-4% over baseline for both scenarios.

Although this standardization increases the value of the fishery in both COMM and TEST scenarios, it does not affect the rank order of the total value of improved information or the value of test fishery information (Figure 23). The mean value of the catch for TEST management is still $660,000 greater than that of the next best alternative, COMM management, which is now $3,000,000 greater than that of PRE management. With or without standardization of commercial C/f, the benefit of TEST management is greater than its cost of $116,000.

Shortened Fishing Season

In Area 4, a commercial fishery for pink salmon (O. gorbuscha) overlaps the latter part of the sockeye fishery (Sprout and Kadowaki 1987). During this period, management actions to optimize sockeye escapement may be constrained by considerations for management of the pink fishery (Walters and Buckingham 1975). I tested the effect of this constraint on the results by shortening the length of the fishing season in the model.

Shortening the fishing season by two weeks results in a downward bias in the in-season forecast when C/f is not standardized. This increases mean annual escapement (Figure 24), increases the deviations from the escapement objective, and decreases the value of the catch relative to baseline (Figure 25). To take the annual allowable catch in the remaining

Figure 23. Annual Benefits (Standardized Commercial C/f). Commercial fishery C/f is standardized for the effect of nominal fishing effort on q.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

STANDARDIZED COMMERCIAL CATCH PER EFFORT

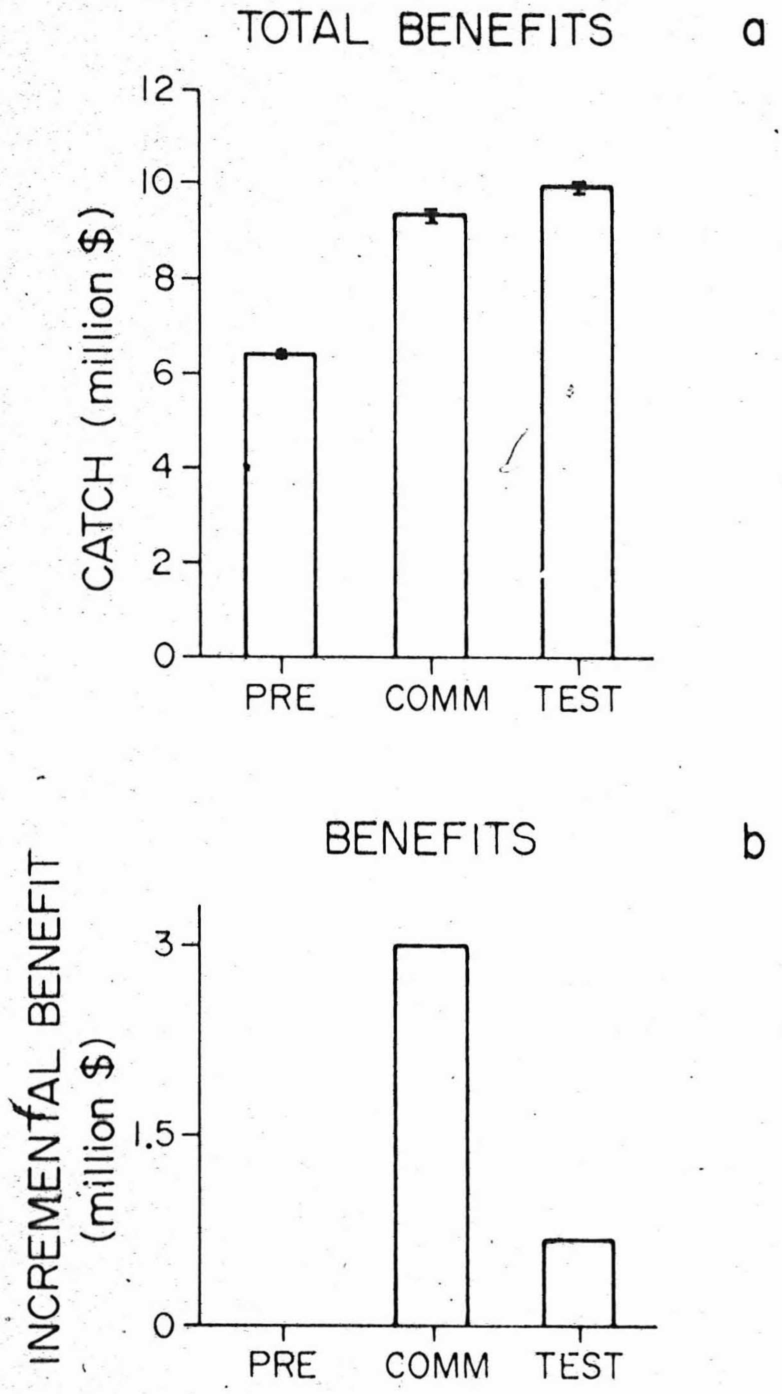


Figure 24. Annual Results (Fishery Shortened by 2 Weeks). Annual results of simulations for the three management scenarios, PRE, COMM, and TEST, compared with historical data (HIST). Fishing season is shortened by 2 weeks. Means and standard deviations (SD) are calculated for number of days open, annual abundance of returns, catch, and escapement. Number of days open is for weeks 6-1 through 8-4 only.

FISHERY SHORTENED BY 2 WEEKS
ANNUAL RESULTS

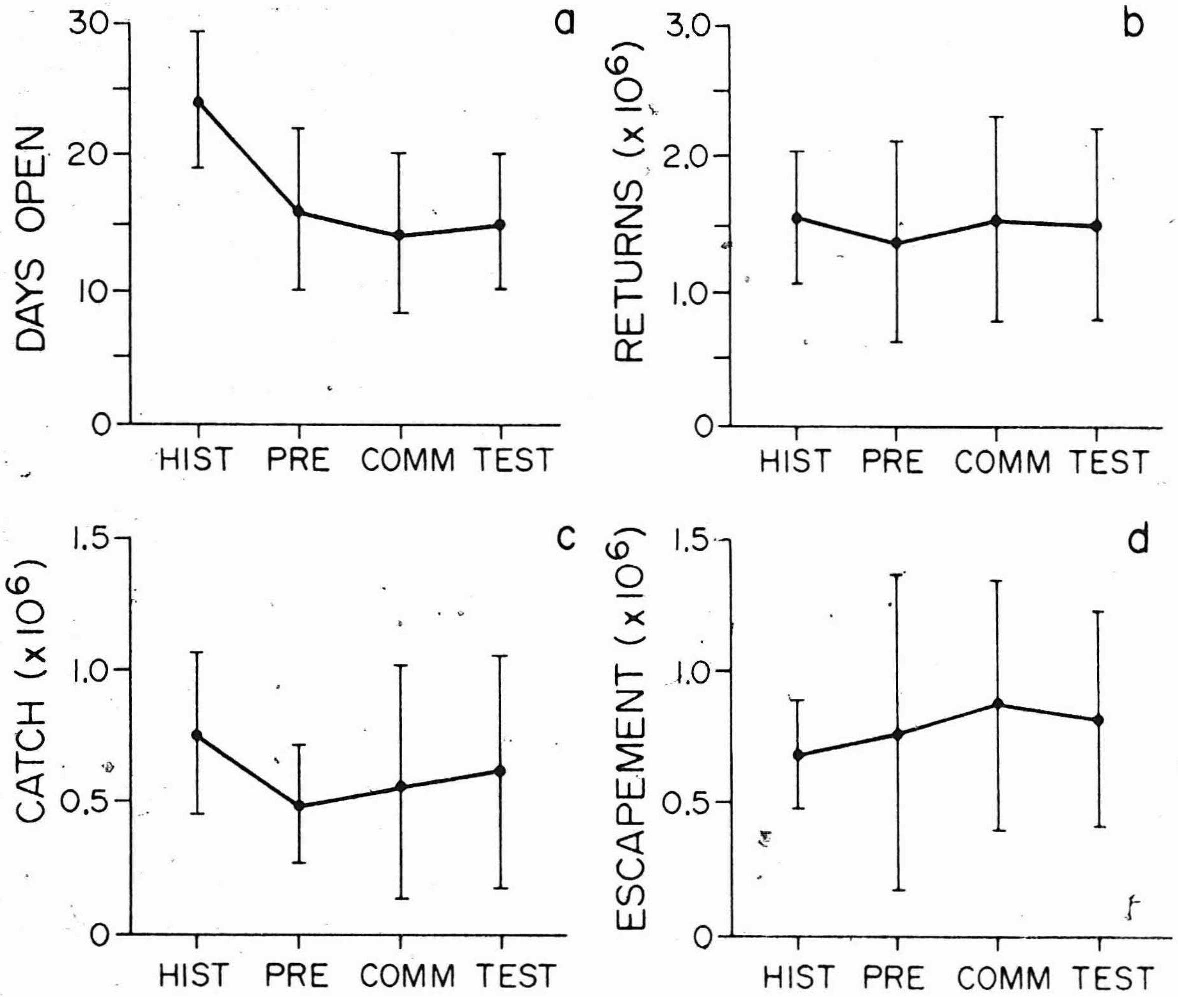
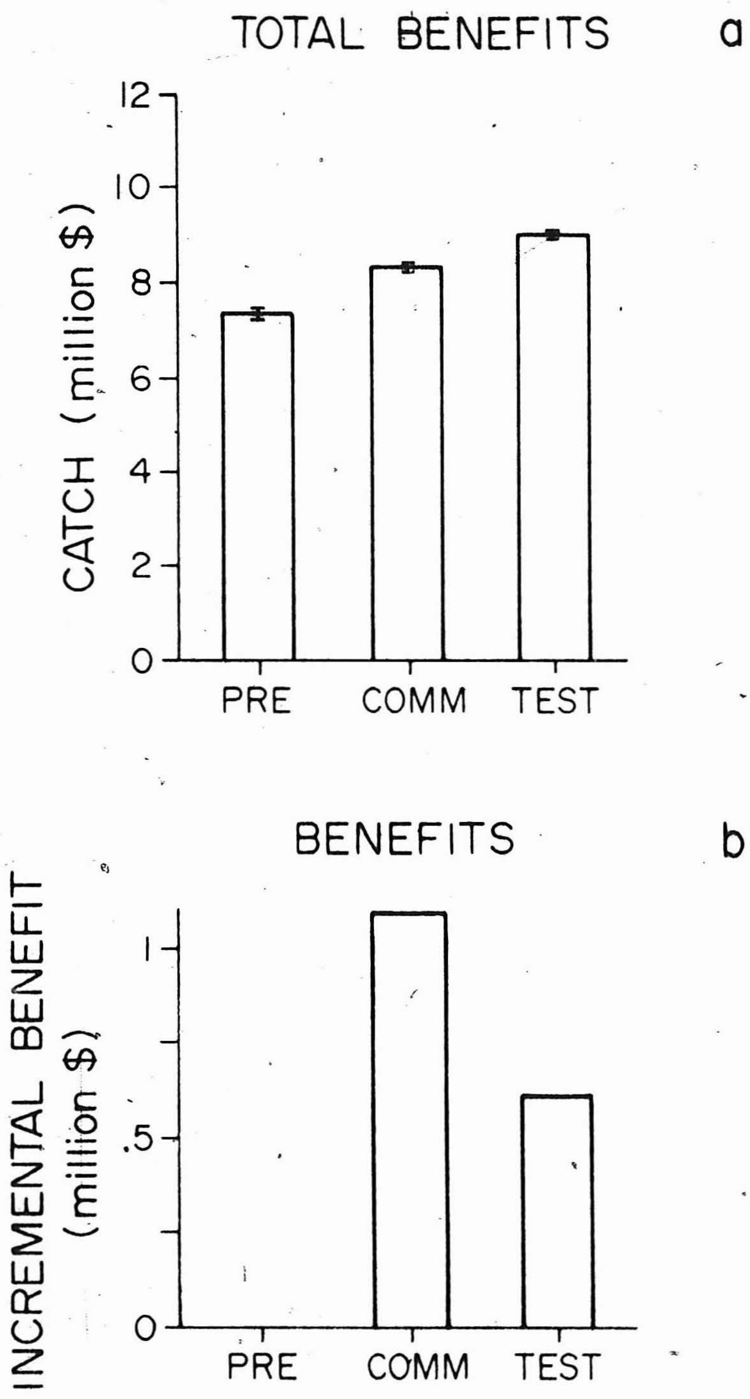


Figure 25. Annual Benefits (Fishery Shortened by 2 Weeks).

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

FISHERY SHORTENED BY 2 WEEKS


TOTAL BENEFITS a

BENEFITS b

openings requires greater fishing effort which depresses q through the harvest rate function (Equation 6). This results in a downward bias in commercial C/f, downward bias in the return forecast, and a greater frequency of fishery closure. Even when commercial C/f is standardized, the value of the catch drops relative to baseline (Figure 26). Curtailing the fishing season reduces the time available to collect test fishery data, which would alter the forecast and reopen the fishery if returns were late.

Although the rank order of the management scenarios does not change from that in the baseline, the curtailment of the fishing season reduces the impact of the forecast from the test fishery so benefits decrease with the shorter season. The mean value of the catch for TEST management is \$350,000 to \$610,000 greater than that of the next best alternative, COMM management, which is \$1,100,000 to \$1,460,000 greater than that of PRE management. Even with a curtailed fishing season, the benefit of TEST management is greater than the mean annual cost of \$116,000.

Improved Pre-season Forecast

Fishery managers may invest in programs to improve the precision of the pre-season forecast. To test the sensitivity of the results to improved pre-season forecasts, I ran the model with the baseline error variance of the pre-season forecast ($2.87X10^{11}$) reduced by 50% and 75%. As expected, results are highly sensitive to the precision of the pre-season forecast.

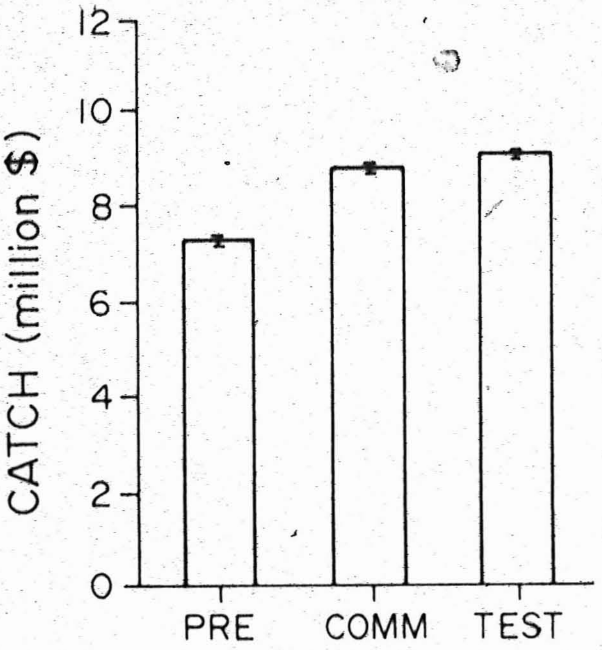
Figure 26. Annual Benefits (Fishery Shortened by 2 Weeks, Standardized Commercial C/f). Fishing season is shortened by 2 weeks and commercial fishery C/f is standardized for the effect of nominal fishing effort on q.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

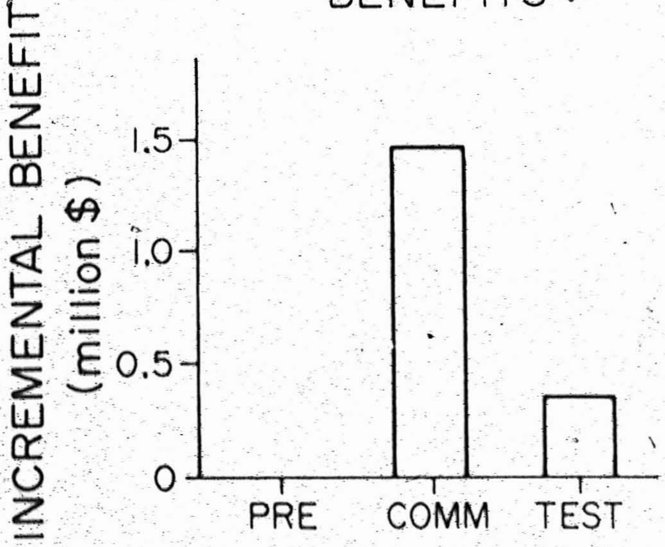
b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

FISHERY SHORTENED BY 2 WEEKS STANDARDIZED COMMERCIAL CATCH PER EFFORT

TOTAL BENEFITS a



BENEFITS b



A 50% reduction in the error variance of the pre-season forecast decreases deviations from the escapement objective (Figure 27), increases mean annual escapement, and increases mean values of the catch in all management scenarios over those in the baseline simulations. It also reduces the benefit of in-season forecasts. Although TEST management still is best without commercial C/f standardization, the rank order of the mean values of the annual catch (Figure 28) changes to TEST ($9.94m) > PRE ($9.76m) > COMM ($9.57m). With commercial fishery C/f standardization, the rank order of the mean values of the annual catch (Figure 29) is unchanged with TEST ($10.16m) > COMM ($9.91m) > PRE ($9.76). The mean value of the catch for TEST management is $180,000 to $250,000 greater than that of the next best alternative. Even with a 50% increase in the precision of the pre-season forecast, the benefit of TEST management is greater than its cost of $116,000.

When the error variance of the pre-season forecast is reduced by 75%, the mean values of the catch increase again for all three scenarios. Without commercial fishery standardization, mean value of the annual catch for PRE management ($10.04m) exceeds those of both COMM ($9.82m) and TEST ($10.01m) management (Figure 30). Because of the bias in the return forecast based on commercial fishery C/f, the in-season forecast does not improve management when the pre-season forecast is relatively precise. The mean value of the catch for TEST management is $130,000 greater than that of the next best alternative, when commercial C/f is standardized (Figure 31).

Figure 27. Annual Results (Improved Pre-season Forecast, $\sigma^2/2$). Annual results of simulations for the three management scenarios, PRE, COMM, and TEST, compared with historical data (HIST). Prediction error of pre-season forecast is reduced by 50%. Means and standard deviations (SD) are calculated for number of days open, annual abundance of returns, catch, and escapement. Number of days open is for weeks 6-1 through 8-4 only.

IMPROVED PRE-SEASON FORECAST, $\sigma^2/2$
ANNUAL RESULTS

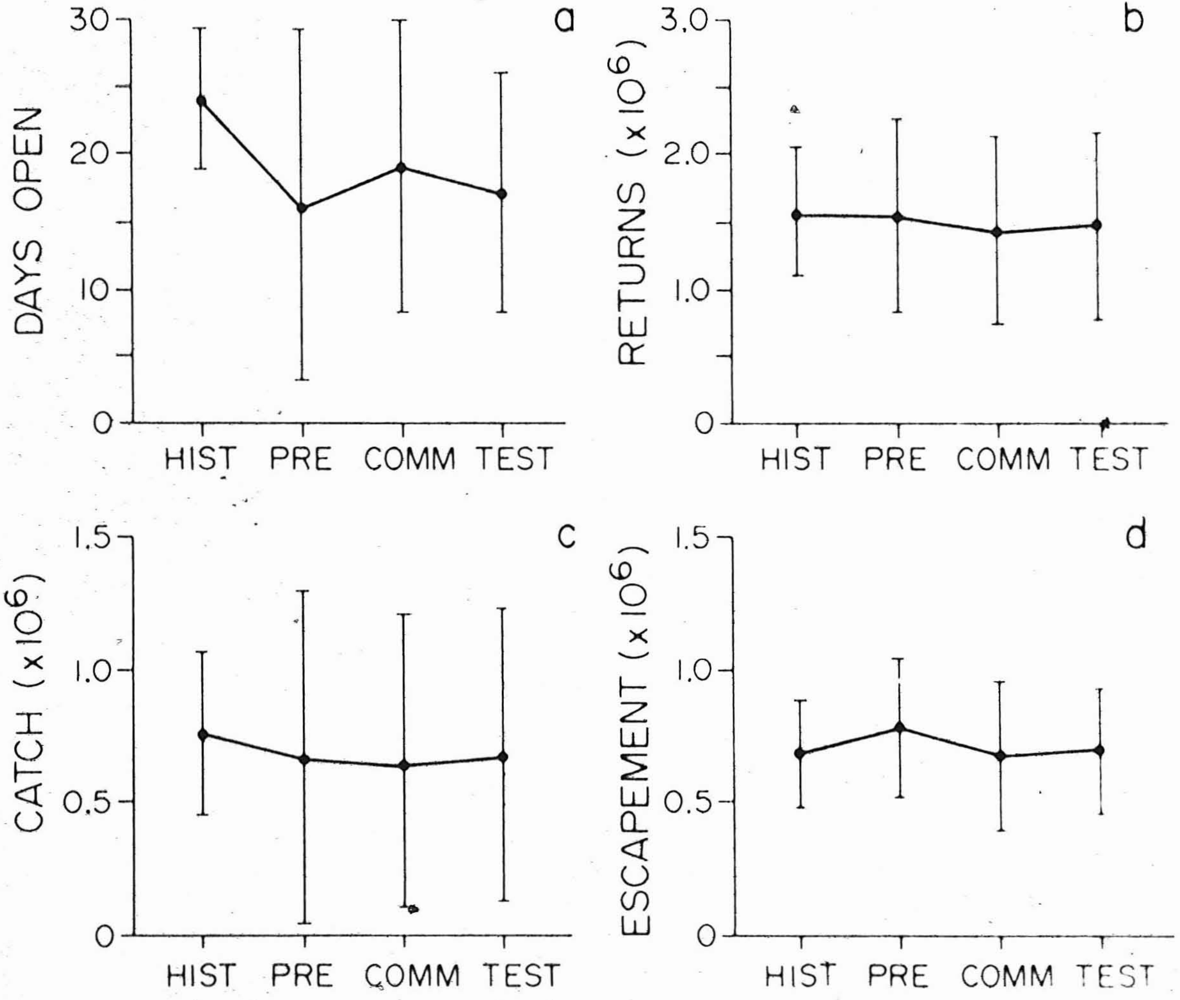


Figure 28. Annual Benefits (Improved Pre-season Forecast, $\sigma^2/2$). Prediction error of pre-season forecast is reduced by 50%.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

IMPROVED PRE-SEASON FORECAST, $\sigma^2/2$

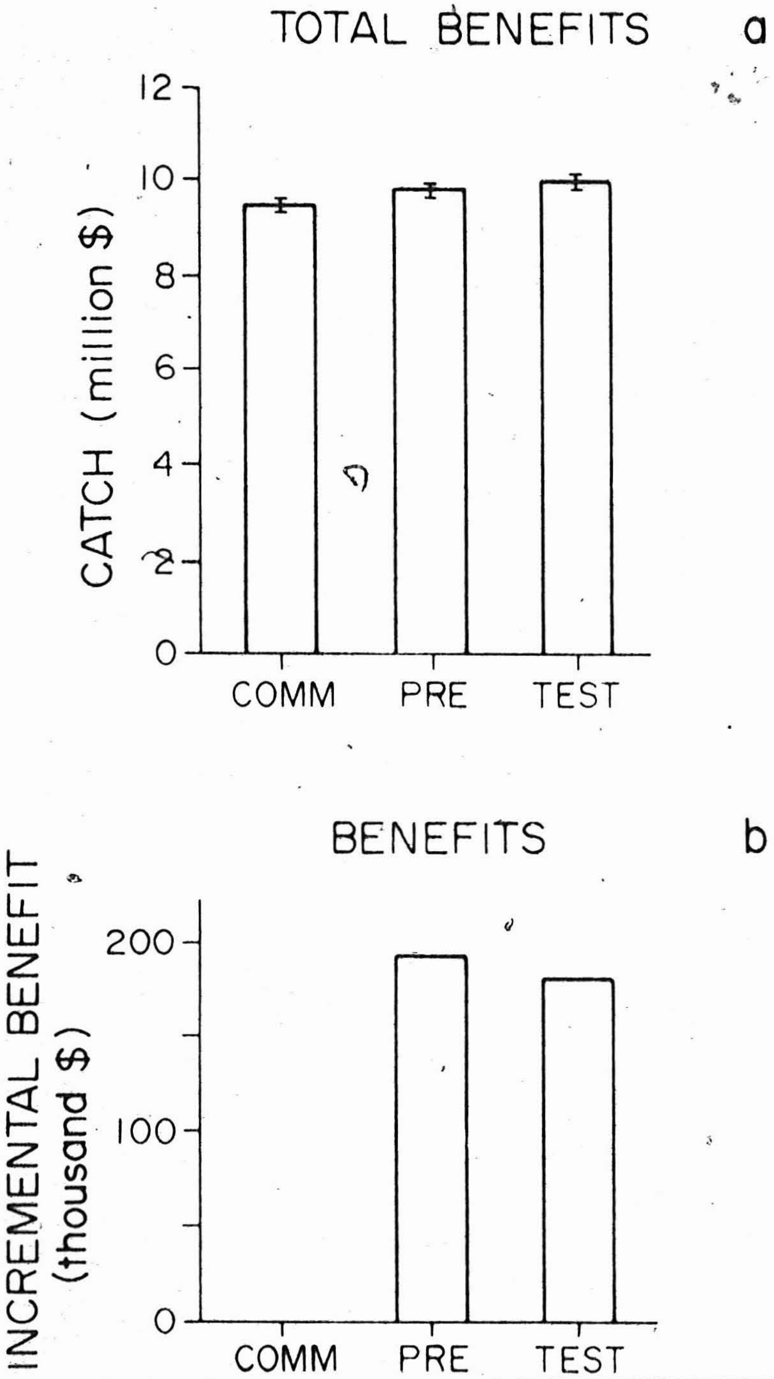


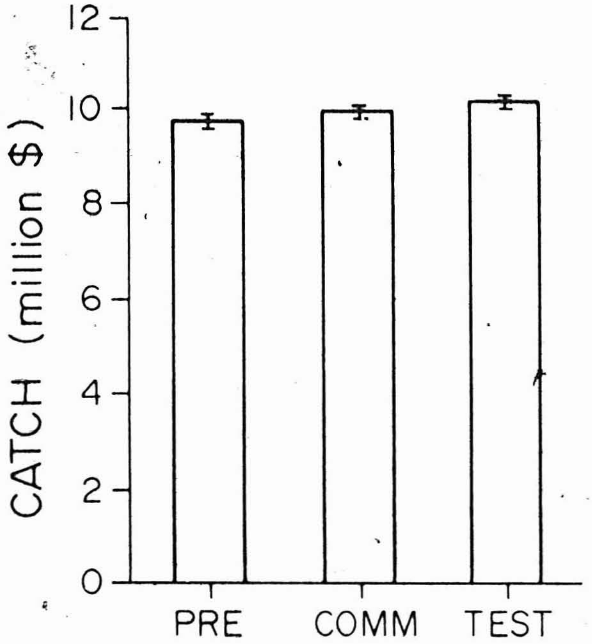
Figure 29. Annual Benefits (Improved Pre-season Forecast, $\sigma^2/2$, Standardized Commercial C/f). Prediction error of pre-season forecast is reduced by 50% and commercial fishery C/f is standardized for the effect of nominal fishing effort on q.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

IMPROVED PRE-SEASON FORECAST, $\sigma^2/2$ STANDARDIZED COMMERCIAL CATCH PER EFFORT

TOTAL BENEFITS a



BENEFITS b

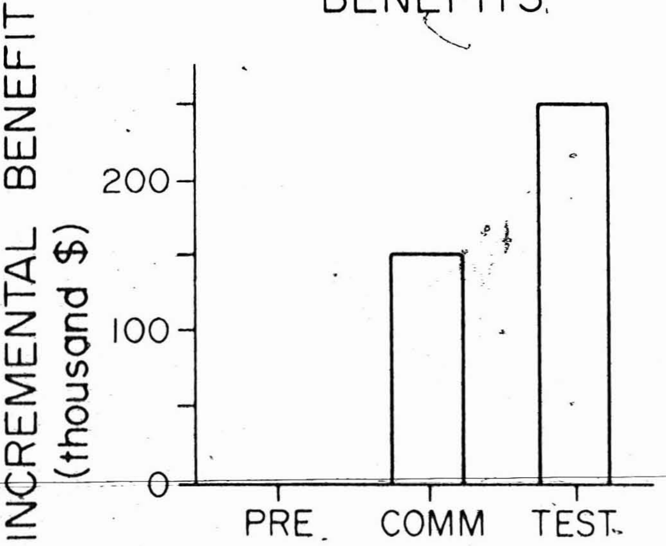


Figure 30. Annual Benefits (Improved Pre-season Forecast, $\sigma^2/4$). Prediction error of pre-season forecast is reduced by 75%.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

IMPROVED PRE-SEASON FORECAST, $\sigma^2/4$

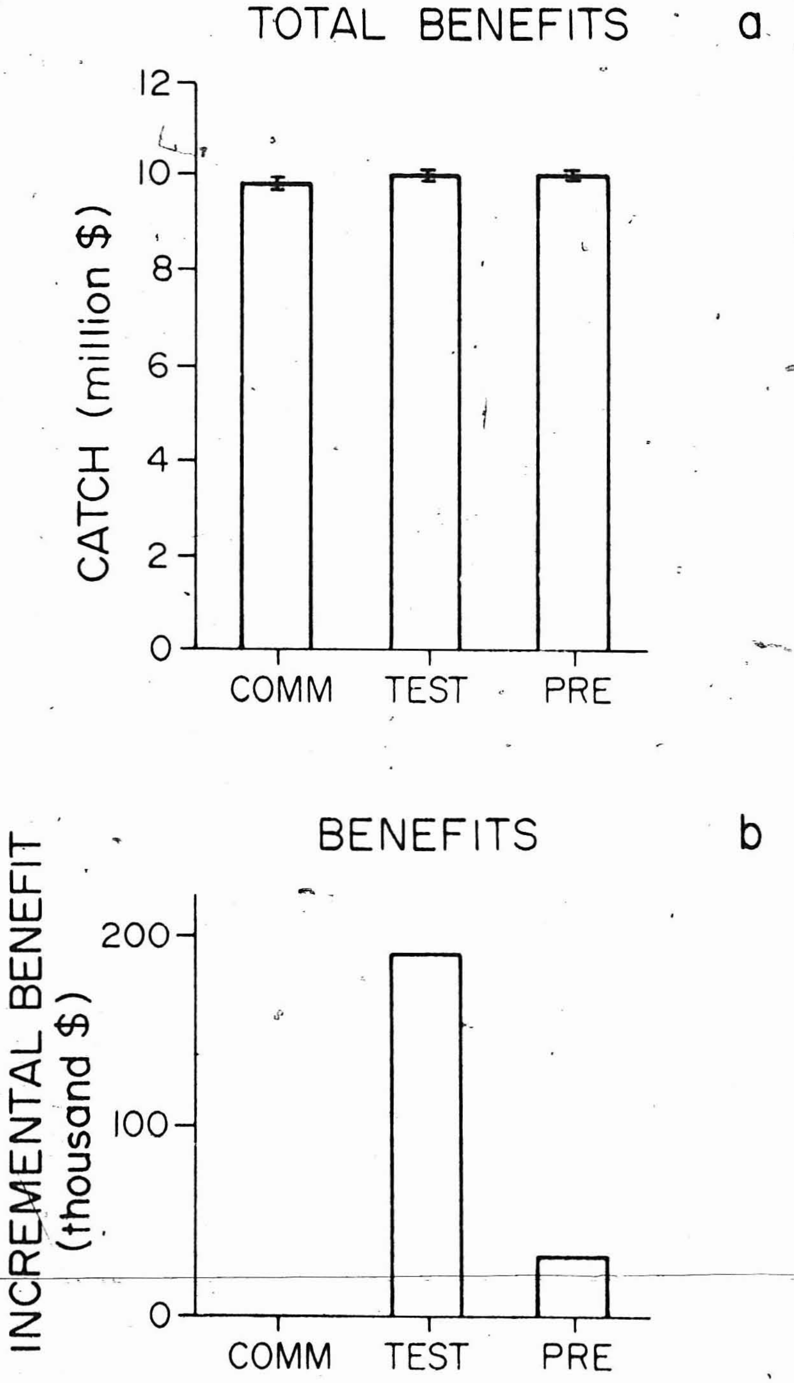
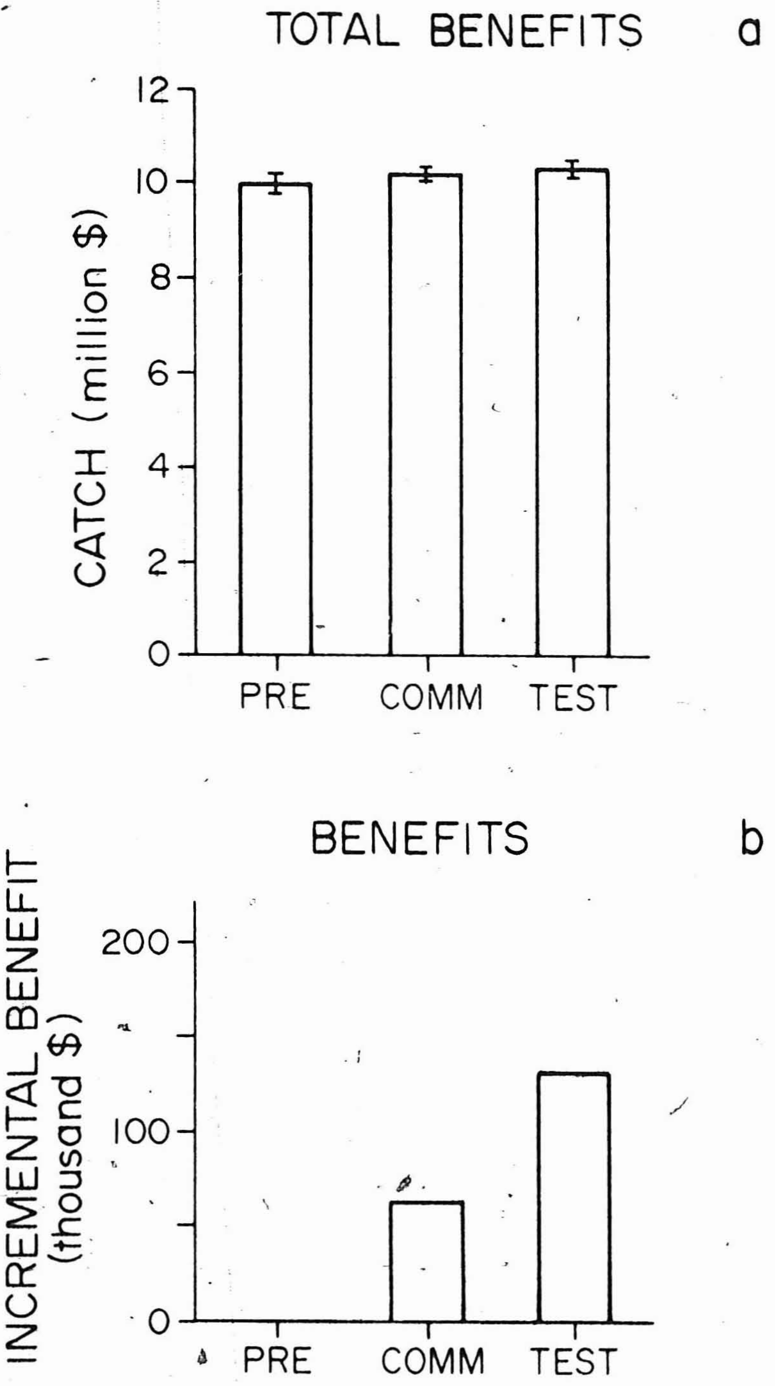


Figure 31. Annual Benefits (Improved Pre-season Forecast, $\sigma^2/4$, Standardized Commercial C/f). Prediction error of pre-season forecast is reduced by 75% and commercial fishery C/f is standardized for the effect of nominal fishing effort on q.

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, and TEST scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

IMPROVED PRE-SEASON FORECAST, $\sigma^2/4$
STANDARDIZED COMMERCIAL
CATCH PER EFFORT



With a 75% increase in the precision of the pre-season forecast, the benefit of TEST management is equal to or less than its cost of $116,000.

Perfect Information

To establish an upper limit on the benefit of return forecast information and harvest control systems, I ran the simulation with (1) perfect knowledge of the abundance of annual returns but imperfect harvest control (PFOR), and (2) perfect knowledge of abundance of annual returns and perfect harvest control to take the annual allowable catch (PERF). The mean value of the catch for PFOR is $10,470,000 and for PERF is $10,670,000 (Figure 32). Perfect control of harvest increases the mean value of catch by only $200,000. These values are respectively $870,000 and $1,070,000 greater than the mean value of the catch for TEST management without commercial fishery C/f standardization, and $490,000 and $690,000 greater than that for TEST management with commercial fishery C/f standardization (Figure 33). These differences represent the benefit of perfect forecasts of returns and the benefit of perfect fishery management to the simulated Area 4 sockeye fishery. They are also the maximum annual amounts that could be spent for improved forecasts of return abundance or improved fishery control and have the benefit exceed the cost of information acquisition.

The mean net present value of the catch (NPV) for PFOR is $113,000,000 and for PERF is $115,000,000. The NPV of PERF management is $4,000,000 greater than that for TEST management

Figure 32. Annual Benefits (Perfect Information). Annual benefits of perfect knowledge of the abundance of annual returns but imperfect harvest control (PFOR) and benefits of perfect knowledge of the abundance of annual returns and perfect harvest control to take the annual allowable catch (PERF).

a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, TEST, PFOR, and PERF scenarios.

b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean annual value of the catch from that of the next best alternative, i.e. the next highest.

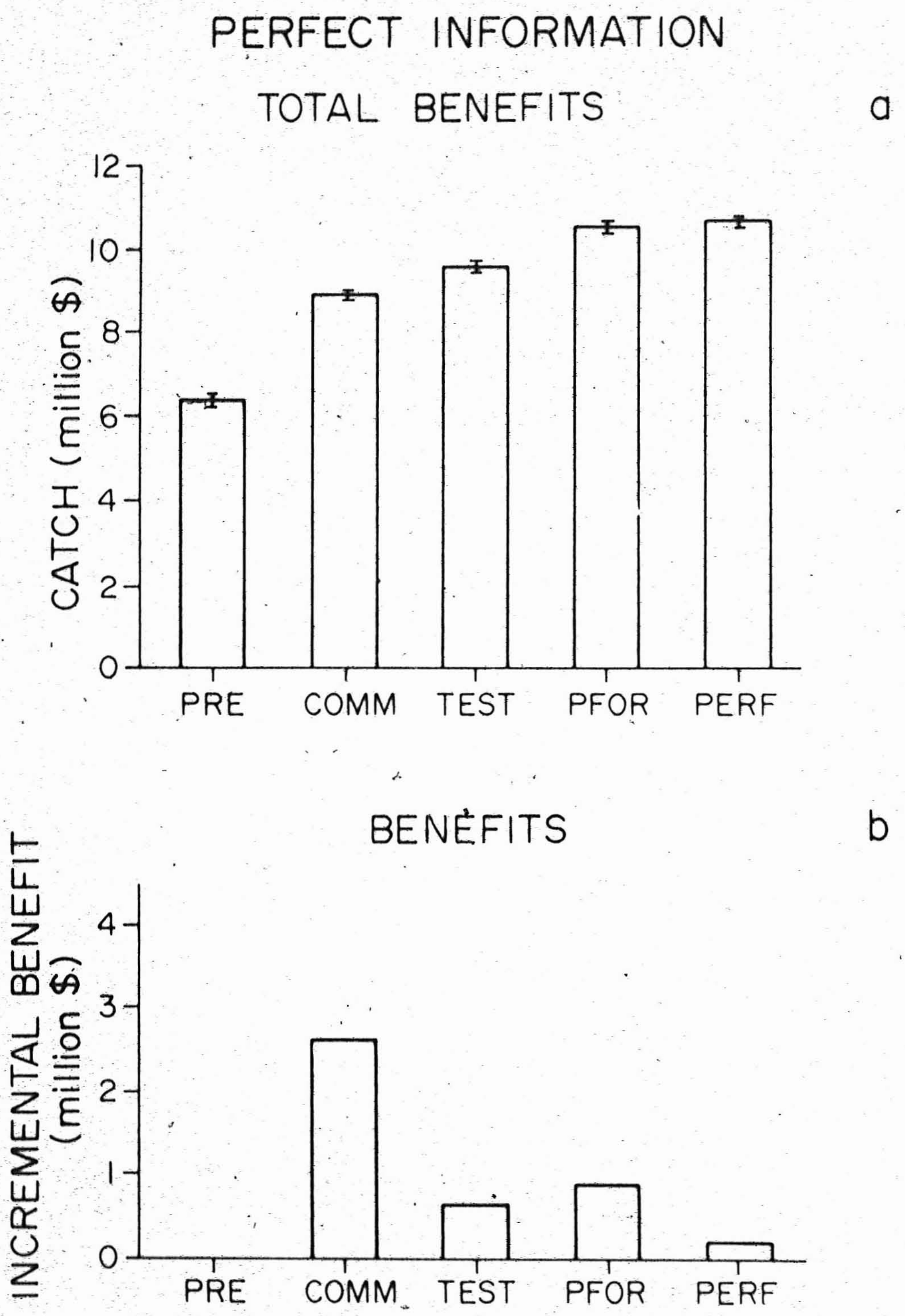
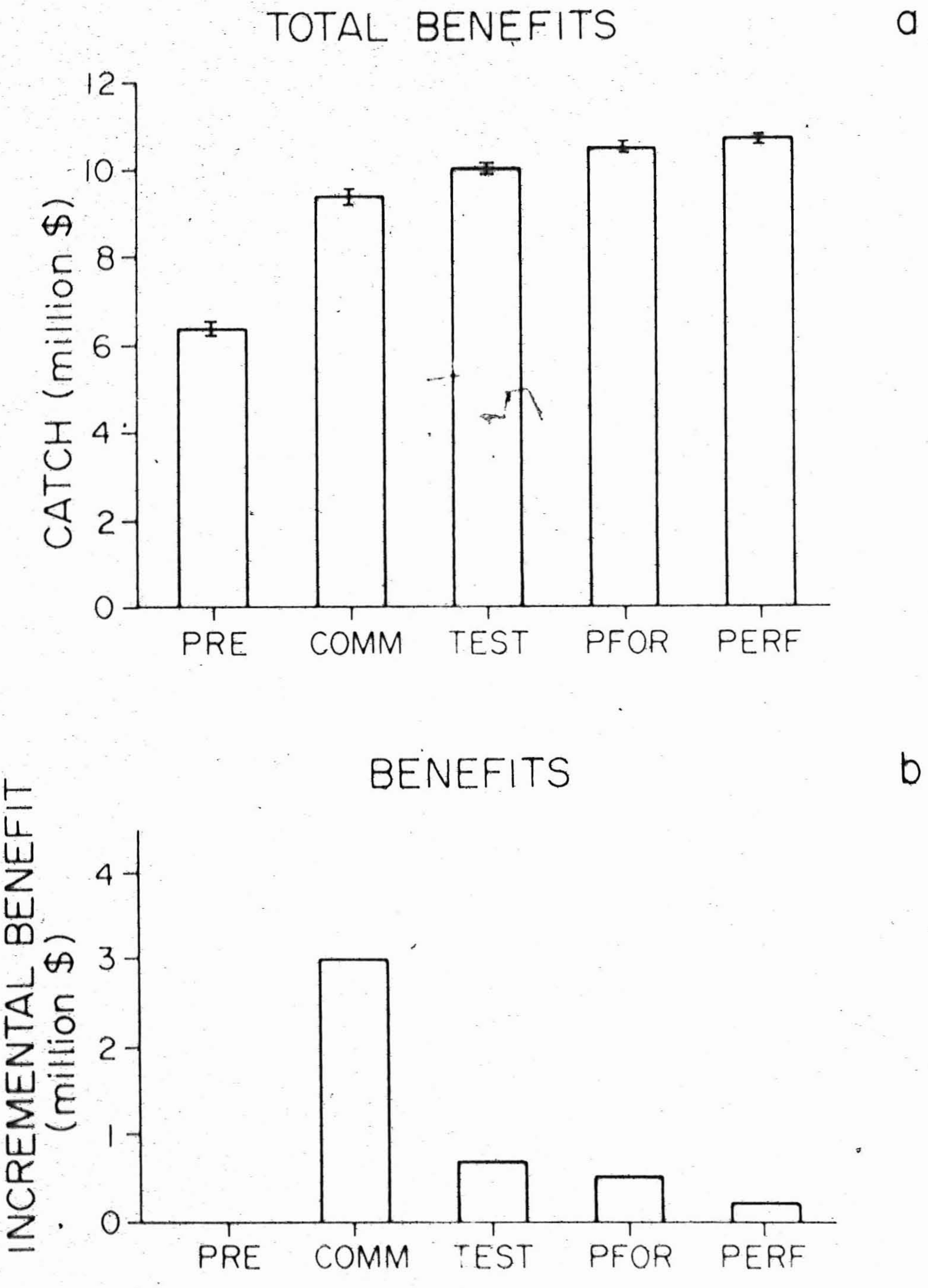

PERFECT INFORMATION
TOTAL BENEFITS
a
CATCH (million $)
0
2
4
6
8
10
12
PRE
COMM
TEST
PFOR
PERF
BENEFITS
b
INCREMENTAL BENEFIT (million $)
0
1
2
3
4
PRE
COMM
TEST
PFOR
PERF

Figure 33. Annual Benefits (Perfect Information, Standardized Commercial C/f). Annual benefits of perfect knowledge of the abundance of annual returns but imperfect harvest control (PFOR) and benefits of perfect knowledge of the abundance of annual returns and perfect harvest control to take the annual allowable catch (PERF). Results are compared with PRE, COMM, and TEST simulations with standardized commercial fishery C/f. a. Total Benefits. Mean and standard error (SE) of annual value of catch for PRE, COMM, TEST, PFOR, and PERF scenarios. b. Benefits of Improved Information. For each scenario, benefit is calculated by subtracting the mean value of the catch from that of the next best alternative, i.e. the next highest.

PERFECT INFORMATION STANDARDIZED COMMERCIAL CATCH PER EFFORT



without commercial fishery C/f standardization and $2,000,000 greater than that for TEST management with commercial fishery C/f standardization. The NPV of PFOR management is $2,000,000 greater than that for TEST management without commercial fishery C/f standardization and approximately equal to that for TEST management with commercial fishery C/f standardization. These amounts represent the maximum that discounted costs of a project could be to improve forecasts of return abundance or improve fishery control and still have the project be economically efficient (benefit > cost).

Discussion

The present test fishery on the Skeena River is economically efficient and thus worth retaining. The cost of operating the test fishery is less than the increase in the mean value of the catch due to management based on test fishery catch per effort (C/f) data over that of management based on commercial fishery C/f data, the next best alternative. Curtailing the fishing season to allow for management of the fishery for pink salmon reduces the benefit of test fishery information but the net benefit remains positive. Only when the precision of the pre-season forecast is improved by 75%, is the benefit of the test fishery less than the cost of its operation.

This benefit results from the continuous operation of the test fishery throughout the salmon run and from the increased precision of the return forecast in the latter part of the fishing season. Management of the sockeye fishery based on commercial fishery C/f is the next best alternative to management based on test fishery C/f. However, if returns were late and the commercial fishery closed, it would not reopen because the in-season forecast would not be updated. Due to the high mortality rate of fish caused by the commercial fishery, leaving it open to provide return information would endanger the escapement objective. In contrast, the low mortality rate caused by the test fishery does not present this conservation problem. Thus, the return forecast would be updated with more precise estimates as the season progressed and the commercial fishery could reopen if returns improved. A test fishery thus reduces the frequency of overescapement, decreases deviations from optimum escapement, increases stock productivity, and increases the value of the catch. Lord (1976) also found that increased precision of in-season forecasts of stock abundance decreased deviations from the escapement objective and increased mean catch.

As expected from the theoretical model relating benefits to precision of information (Figure 2), although total benefit increases with increasing precision of forecasts and control of the fishery (Figures 32, 33), the amount of additional benefit gained by going to each next more precise method declines. The cost of perfect forecasts is likely higher than their benefit, $490,000. In this case, since the net benefit of test fishery information is positive and the net benefit of the next more precise option is likely negative, TEST management is the economic optimum among the options presented here. Mathews (1971) contended that the cost of moving from a moderately accurate pre-season forecast (+/- 50% error) to an accurate forecast (+/- 10% error) was likely greater than its benefit. Walters and Buckingham (1975) also found that perfect pre-season forecasts resulted in little improvement in control of exploitation rates in their model of the Area 4 salmon fishery, but they did not do an economic analysis.

Although the test fishery provides an economically significant benefit, the improvement in mean catch is relatively small and would be extremely difficult to detect in a given set of data on two systems (one with test fishery data and one without) due to the high variance of annual catch. This is no surprise given the small change (7%) in the mean annual catch relative to the variance of the annual catch. For example, the difference in mean annual catch between TEST and COMM scenarios in the baseline simulations is 45,000 fish. The standard deviation of the annual catch from the historical data is 307,000 fish. To statistically detect the difference in the two means would require an unreasonably long period of assessment, more than 700 years. However, although the increase in catch is statistically difficult to detect, it is economically significant. The net annual benefit of having a test fishery is between $234,000 and $544,000, i.e. the increase in catch is that much more than the cost of the test fishery. Even with perfect management, comprised of exact knowledge of return abundance and perfect control of the fishery to harvest the allowable catch, the increase in mean catch over COMM management is relatively small (19%) and substantial year-to-year variation remains. Assessments based on short time series thus would not detect the benefits of improved forecasting and fishery control systems.

Statistical evaluation of historical data from fisheries management systems will have low power to detect economically significant results, given levels of natural variability in stock-recruitment similar to that of the Area 4 sockeye stock. High background variability will produce Type II statistical errors, the acceptance of the null hypothesis of no difference when in fact a difference exists. Others have shown that low statistical power may mask declines in fish populations. Peterman and Bradford (1987) showed that low statistical power, resulting from natural variation in population processes and errors in stock assessment methods, reduced the probability of detecting time trends in fish populations which could lead to population collapse. I show here that it may also mask increases in fish catches and that it may result in the termination of fishery management or stock development initiatives that are economically efficient (benefit > cost).

One way of increasing the power of the test is to increase the sample size, i.e. increase the duration of the evaluation period. However, given the level of variability of returns of Area 4 sockeye, the evaluation period would stretch well beyond the career of the assessment biologist and certainly beyond any reasonable funding horizon.

Thus, simulation or analytic models are a necessary first step in the process of evaluating benefits from changes in fishery management because of the difficulty in directly measuring their effects in the field. Simulation models are powerful tools for testing stock assessment and management techniques against "known" systems (Hilborn and Walters 1988) and can be used to estimate the magnitude of mean change in benefits and its variability. This information can then be used to determine the feasibility of an experiment to directly measure the change and to control expectations of likely outcomes by providing information on the statistical power of the design (Peterman and Bradford 1987).

List of References

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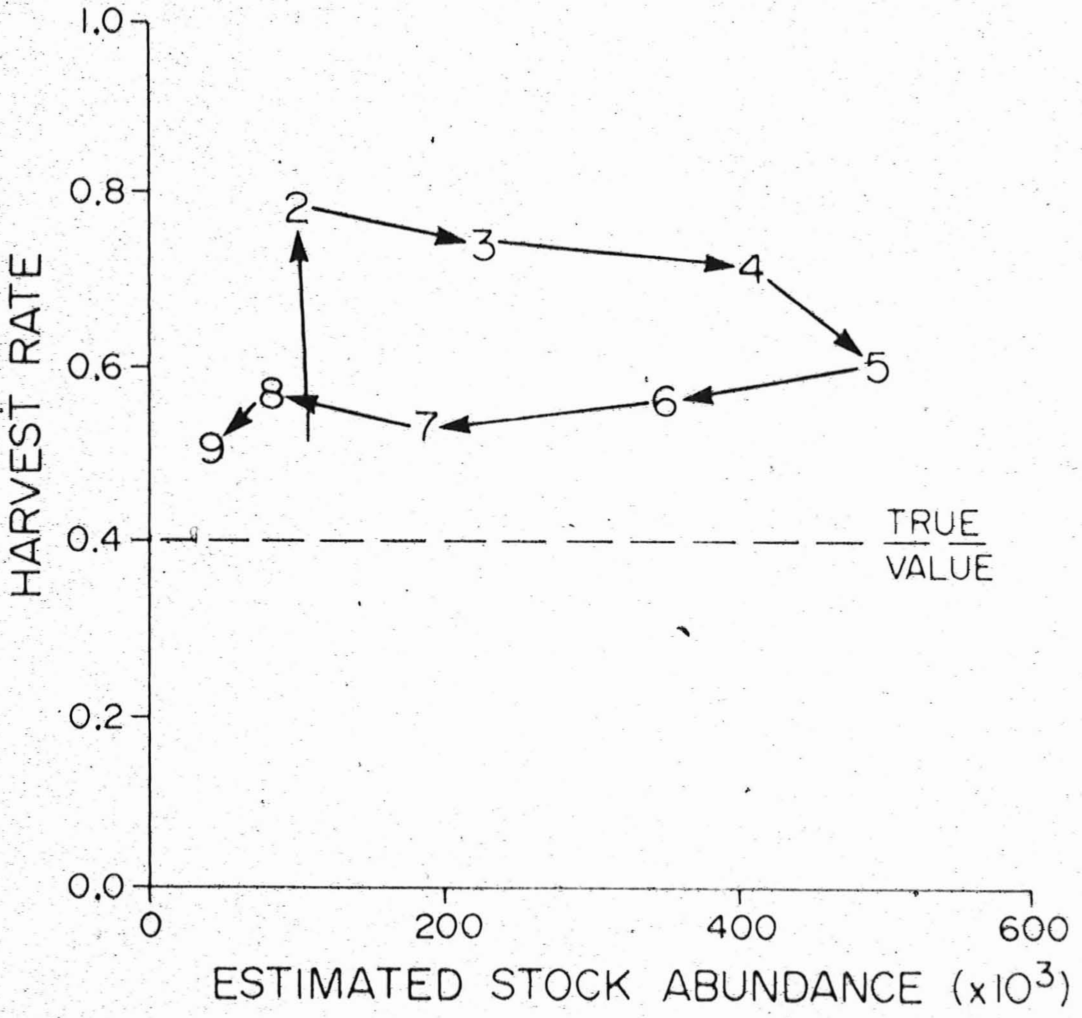
Appendix A. Simulated Effect on Harvest Rate of Sockeye Pooling in Area 4.

In my analysis of the components of the catch equation for the commercial gillnet fishery in Area 4, I assume that sockeye do not pool, i.e. they are vulnerable to the fishery for only one week. If sockeye pool in the commercial fishing area, simply adding weekly catch to weekly escapement will underestimate fish abundance and thus inflate the harvest rate. To illustrate this bias, I arbitrarily selected the return timing data from 1978 and used these data in a simple model that simulated fish pooling in the commercial fishing area for 2 weeks before heading upriver. I assumed a run size of $2.0X10^6$ fish and a harvest rate of 0.4. Basically, the model calculated the catch from the 2 weeks of fish vulnerable to the fishery, calculated the escapement only from the group of fish that had been in the fishery for 2 weeks, and then estimated the abundance of fish in the fishing area (catch plus escapement) and the apparent harvest rate.

The apparent weekly harvest rates are greater than the actual harvest rate used in the simulation (Figure A1), reflecting the downward bias in the estimate of fish abundance in the fishing area. This estimate of fish abundance is composed only of fish in the catch and the escapement and does not include pooled fish, those that were not harvested but remained in the fishing area. This pool of fish is subject to another fishery the next

Figure A1. Simulated effect on harvest rate of fish pooling for 2 weeks on the fishing grounds. Arrows indicate time sequence of weekly harvest rates. Week 1 is week 6-4, the last week in June.

EFFECT ON HARVEST RATE OF 2 WEEK POOLING



week before migrating out of the fishing grounds. The downward bias in the estimate of fish abundance, the denominator in the calculation of harvest rate, inflates the harvest rate. The magnitude of this bias tends to be highest early in the season. Early in the season, weekly returns to the fishery increase with time such that the proportion of actual fish abundance not accounted for in the estimate of fish abundance is largest early in the season. After weekly returns to the fishery peak, the proportion of fish not accounted for in the estimate of fish abundance is lower and the magnitude of bias is reduced.

If fish pool, then estimates of the catchability coefficient (q) early in the season will be biased upward relative to those later in the season. If fishing effort is constant, harvest rate is proportional to q. If an analysis of the functional response used data only from weeks prior to the week of peak abundance, q associated with low stock abundance could be biased upward relative to that associated with high stock abundance. In figure A1, harvest rate or q decreases with increasing apparent stock abundance for the second through sixth weeks. This would result in a positive intercept for a linear model fit to these data and in apparent density dependence for a power model. If data were from weeks throughout the season, mean q would not decrease with increased stock abundance. In figure A1, there is no relationship between harvest rate or q and apparent stock abundance. However, the residuals from the functional response would decrease with week. Because I used data from weeks throughout the run I do not expect that my finding of apparent density-dependent q is the result of fish pooling. The results from the simulations should be unbiased because the functions in the submodels are internally consistent. The functions in the sockeye dynamics, fishing fleet dynamics, and management submodels all assume no pooling.

Appendix B. Determination of Sockeye Migration Lag from Area 4 to Test Fishery.

There should be no migration lag for sockeye travelling from the commercial fishing area to the test fishery site because the test fishery is located immediately upstream from the commercial fishing boundary. To test this, I calculated coefficients of determination for both linear and asymptotic nonlinear models applied to the weekly commercial gillnet and seine functional responses. I found that the strongest relationship between catch per unit effort and stock abundance occurred when the escapement data are not lagged.

	Gillnet			Seine		
Lag (d)	n	$C/f=a*N^b$	$C/f=a+bN$	n	$C/f=a*N^b$	$C/f=a+bN$
0	65	0.909	0.791	10	0.919	0.907
1	62	0.864	0.787	10	0.906	0.895
2	62	0.870	0.790	10	0.906	0.896
3	61	0.854	0.784	10	0.905	0.889
4	60	0.877	0.780	10	0.901	0.876
5	57	0.882	0.788	10	0.892	0.858

Appendix C. Correction for Measurement Error of Parameters and Variances Estimated by Linear Regression.

The measurement error variance is used to correct the downward bias in the positive slope of the weekly functional response as follows (Peterman et al. 1985). Let

(1) $\gamma = \sigma^2_e / (\sigma^2_x - \sigma^2_e)$

where σ^2_x = variance of the observed independent variate (weekly abundance of sockeye) and σ^2_e = variance of the measurement error of the independent variate. Then the corrected slope, B, is

(2) $B = b * (1 + \gamma)$

where b = estimated slope from least squares regression, with standard error

(3) $s_B = \sqrt{(\sigma^2_{yx} / s^2_{xx})}$

with

(4) $s^2_{xx} = (\sigma^2_x - \sigma^2_e)(n - 1)$

(5) $\sigma^2_{yx} = \sigma^2_y - (\sigma^2_y - \sigma^2_{yx'})(1 + \gamma)$

where σ^2_y = variance of the dependent variate, $\sigma^2_{yx'}$ = estimated variance of the regression, and n = number of points.

I calculate the true intercept, A, as

(6) A = ybar - B * xbar

where ybar = mean of the dependent variate and xbar = mean of the independent variate, with standard error

$$s_A = \sqrt{(\sigma^2_{yx} (1 + xbar^2 / s^2_{xx} - 1/n))} \quad (7)$$

Appendix D. Analysis of Covariance for Differences in Functional Response of Gillnet Fleet by Opening Length.

Hypothesis 1 : Are slopes equal?

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_1x_2 + b_7x_1x_3 + b_8x_1x_4 + b_9x_1x_5 + b_{10}x_6$$

where $y = \ln(C/f)$
$x_1 = \ln(\text{sockeye abundance})$
$x_2 = 1$ if 1 day opening, 0 otherwise
$x_3 = 1$ if 2 day opening, 0 otherwise
$x_4 = 1$ if 3 day opening, 0 otherwise
$x_5 = 1$ if 4 day opening, 0 otherwise
$x_6 = 1$ if 5 day opening, 0 otherwise

$H_0 : b_6 = b_7 = b_8 = b_9 = 0$
$H_1 : b_6 <> b_7 <> b_8 <> b_9 <> 0$

$F_{4,55} = 1.369$ $P > 0.05$ Accept H_0

Hypothesis 2 : Are intercepts equal?

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5$$

$H_0 : b_2 = b_3 = b_4 = b_5 = 0$
$H_1 : b_2 <> b_3 <> b_4 <> b_5 <> 0$

$F_{4,59} = 2.635$ $P < 0.05$ Reject H_0
$P(b_5=0) = 0.0308$

Hypothesis 3 : Is the intercept for the 4 day opening functional response different from that for the combined 1,2,3 and 5 day opening functional response?

$$y = b_0 + b_1x_1 + b_4x_4$$

$H_0 : b_4 = 0$
$H_1 : b_4 <> 0$

$P(b_4=0) = 0.13$ Accept H_0

Conclusion: The functional response of the gillnet fleet as estimated using the asymptotic nonlinear model is not significantly different between openings of different lengths.

Appendix E. Tables of Weekly and Annual Results from Simulations.

Table E1. Baseline Weekly Results. Weekly results of 100 simulations of 50 yr duration with baseline conditions for the three management scenarios, PRE, COMM, and TEST, compared with historical data for Area 4, 1966-80. Means and standard deviations (SD) of number of gillnet vessels and number of days open are calculated with values from all weeks; those of catch and C/f are calculated only with values from weeks in which the fishery was open.

		Historical		PRE		COMM		TEST	
Wk	Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
7-2	# Gillnets	356	148	359	146	376	147	378	147
	Days open	2.5	0.5	2.7	0.4	2.8	0.3	2.6	0.4
	Catch (10^3)	59	36	55	62	68	67	67	64
	C/f	68	24	56	50	65	50	70	53
7-3	# Gillnets	477	116	445	189	481	191	484	189
	Days open	3.5	1.2	3.2	1.9	2.5	2.4	2.8	2.5
	Catch (10^3)	156	95	117	113	180	158	189	160
	C/f	88	24	105	116	144	124	134	113
7-4	# Gillnets	527	137	456	184	493	184	497	182
	Days open	3.3	1.4	3.1	2.1	3.4	2.6	3.8	2.2
	Catch (10^3)	168	106	120	104	197	145	179	137
	C/f	97	36	116	131	104	90	115	97
7-5	# Gillnets	562	108	443	182	477	181	481	179
	Days open	3.1	1.6	3.1	2.4	3.1	2.5	3.2	2.4
	Catch (10^3)	173	113	99	84	176	140	178	145
	C/f	88	31	106	134	107	95	116	93
8-1	# Gillnets	539	114	401	166	427	168	430	167
	Days open	2.7	1.6	3.2	2.8	3.2	2.7	2.7	2.6
	Catch (10^3)	122	75	68	62	122	108	125	108
	C/f	70	32	73	103	85	95	107	108
8-2	# Gillnets	452	144	335	142	347	146	348	146
	Days open	2.1	1.3	3.7	3.3	4.5	3.1	2.3	2.9
	Catch (10^3)	63	77	28	39	53	75	77	92
	C/f	47	39	26	53	26	38	51	81

Table E2. Baseline Annual Results. Annual results from 100 simulations of 50y duration for the three management scenarios, PRE, COMM, and TEST, compared with historical data for Area 4, 1966-80. Due to fishery strikes in 1973 and 1975, these years were omitted from statistics on annual catch, escapement, and number of days open. Means and standard deviations (SD) are calculated for annual abundance of returns (Ret), catch (Cat), escapement (Esc) and number of days open. Number of days open is for weeks 6-1 through 8-4 only. Means and standard errors (SE) are calculated for annual value of catch and net present discounted value (NPDV), discounted at 10% per year. For each scenario, marginal value of catch and marginal net present discounted value are calculated by subtracting the mean value of the catch and the mean net present discounted value from those of the next best alternative, i.e. the next highest.

	Historical		PRE		COMM		TEST	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ret (10^3)	1561	481	1149	772	1393	732	1420	707
Cat (10^3)	754	307	430	248	608	527	653	493
Esc (10^3)	684	207	624	613	685	386	667	296
Days open	24	5	19	11	20	11	17	8
			Mean	SE	Mean	SE	Mean	SE
Catch Value ($\$10^6$)			6.32	0.05	8.94	0.11	9.60	0.10
Marginal Value ($\$10^6$)			-		2.62		0.66	
NPDV ($\$10^6$)			90	2.2	105	3.3	111	3.2
Marginal Benefit ($\$10^6$)			-		15		6	

Table E3. Weekly Results (Standardized Commercial C/f). Weekly results of 100 simulations of 50 yr duration with baseline conditions for the three management scenarios, PRE, COMM, and TEST, compared with historical data for Area 4, 1966-80. Simulations are run with standardization of the commercial fishery C/f for effect of nominal fishing effort on q (See In-season Forecast of Annual Abundance of Returns for details). Statistics are as in Table E1.

		Historical		PRE		COMM		TEST	
Wk	**Variable**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
7-2	# Gillnets	356	148	359	146	380	148	381	147
	Days open	2.5	0.5	2.7	0.4	2.9	0.3	2.7	0.4
	Catch (10^3)	59	36	55	62	72	69	70	65
	C/f	68	24	56	50	66	50	71	53
7-3	# Gillnets	477	116	445	189	489	193	491	191
	Days open	3.5	1.2	3.2	1.9	2.9	2.6	2.9	2.6
	Catch (10^3)	156	95	117	113	193	167	198	167
	C/f	88	24	105	116	134	112	136	116
7-4	# Gillnets	527	137	456	184	502	184	504	183
	Days open	3.3	1.4	3.1	2.1	3.1	2.7	3.5	2.4
	Catch (10^3)	168	106	120	104	200	157	182	146
	C/f	97	36	116	131	120	110	129	114
7-5	# Gillnets	562	108	443	182	485	181	487	180
	Days open	3.1	1.6	3.1	2.4	2.9	2.6	3.1	2.6
	Catch (10^3)	173	113	99	84	193	162	191	158
	C/f	88	31	106	134	119	103	120	96
8-1	# Gillnets	539	114	401	166	433	169	435	168
	Days open	2.7	1.6	3.2	2.8	3.0	2.7	2.9	2.7
	Catch (10^3)	122	75	68	62	136	129	144	132
	C/f	70	32	73	103	83	76	98	87
8-2	# Gillnets	452	144	335	142	350	147	351	147
	Days open	2.1	1.3	3.7	3.3	3.8	3.3	2.4	3.0
	Catch (10^3)	63	77	28	39	57	83	85	101
	C/f	47	39	26	53	30	52	50	55

Table E4. Annual Results (Standardized Commercial C/f). Annual results from 100 simulations of 50 yr duration for the three management scenarios, PRE, COMM, and TEST, compared with historical data for Area 4, 1966-80. Simulations are run with standardization of the commercial fishery C/f for effect of nominal fishing effort on q (See In-season Forecast of Annual Abundance of Returns for details). Statistics are as in Table E2.

Commercial Fishery C/f Standardized

	Historical		PRE		COMM		TEST	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ret (10^3)	1561	481	1149	772	1452	726	1465	709
Cat (10^3)	754	307	430	248	634	610	679	567
Esc (10^3)	684	207	624	613	718	346	686	235
Days open	24	5	19	11	19	12	17	10
			Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**
Catch Value ($\$10^6$)			6.32	0.05	9.32	0.13	9.98	0.12
Marginal Value ($\$10^6$)			-		3.00		0.66	
NPDV ($\$10^6$)			90	2.2	107	3.6	113	3.5
Marginal Benefit ($\$10^6$)			-		17		6	

Table E5. Shortened Fishing Season. Annual results of 100 simulations of 50 yr duration with the fishing season shortened by one and two weeks so that fishery ends by week 8-1 and week 7-5, respectively.

Fishery Shortened by 1 Week

	Historical		PRE		COMM		TEST	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ret (10^3)	1561	481	1193	758	1440	742	1450	719
Cat (10^3)	754	307	453	249	599	497	643	473
Esc (10^3)	684	207	643	597	741	426	706	332
Days open	24	5	17	9	16	8	16	7

	PRE		COMM		TEST	
	Mean	SE	Mean	SE	Mean	SE
Catch Value ($\$10^6$)	6.66	0.05	8.81	0.10	9.45	0.10
Marginal Value ($\$10^6$)	-		2.15		0.64	
NPDV ($\$10^6$)	92	2.3	101	3.1	108	3.2
Marginal Benefit ($\$10^6$)	-		9		7	

Fishery Shortened by 2 Weeks

	Historical		PRE		COMM		TEST	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ret (10^3)	1561	481	1364	758	1541	761	1530	747
Cat (10^3)	754	307	496	240	571	447	612	442
Esc (10^3)	684	207	768	596	870	476	817	404
Days open	24	5	16	6	14	6	15	5

	PRE		COMM		TEST	
	Mean	SE	Mean	SE	Mean	SE
Catch Value ($\$10^6$)	7.29	0.05	8.39	0.09	9.00	0.09
Marginal Value ($\$10^6$)	-		1.1		0.61	
NPDV ($\$10^6$)	90	2.3	93	2.7	100	2.8
Marginal Benefit ($\$10^6$)	-		3		7	

Table E6. Shortened Fishing Season (Standardized Commercial C/f). Annual results of 100 simulations of 50y duration with the fishing season shortened by one and two weeks so that fishery ends by week 8-1 and week 7-5, respectively. Simulations are run with standardization of the commercial fishery C/f for effect of nominal fishing effort on q.

Fishery Shortened by 1 Week

	Historical		PRE		COMM		TEST	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ret (10^3)	1561	481	1193	758	1463	729	1485	719
Cat (10^3)	754	307	453	249	624	583	666	541
Esc (10^3)	684	207	643	597	739	375	720	282
Days open	24	5	17	9	17	10	16	8
			Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**
Catch Value ($\$10^6$)			6.66	0.05	9.18	0.12	9.79	0.11
Marginal Value ($\$10^6$)			-		2.52		0.61	
NPDV ($\$10^6$)			92	2.3	104	3.4	110	3.4
Marginal Benefit ($\$10^6$)			-		12		6	

Fishery Shortened by 2 Weeks

	Historical		PRE		COMM		TEST	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ret (10^3)	1561	481	1364	758	1541	753	1544	748
Cat (10^3)	754	307	496	240	595	506	619	473
Esc (10^3)	684	207	768	596	845	430	825	392
Days open	24	5	16	6	15	8	15	7
			Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**
Catch Value ($\$10^6$)			7.29	0.05	8.75	0.11	9.10	0.10
Marginal Value ($\$10^6$)			-		1.46		0.35	
NPDV ($\$10^6$)			90	2.3	97	3.0	101	2.9
Marginal Benefit ($\$10^6$)			-		7		4	

Table E7. Improved Pre-season Forecast ($\sigma^2/2$). Annual results of 100 simulations of 50 yr duration with precision of the pre-season forecast of abundance of returns increased by factor of 2. Simulations are run with and without standardization of the commercial fishery C/f for effect of nominal fishing effort on q.

Commercial Fishery C/f Not Standardized

	Historical		PRE		COMM		TEST	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Re (10^3)	1561	481	1544	728	1423	711	1467	704
Cat (10^3)	754	307	664	634	651	554	676	557
Esc (10^3)	684	207	780	269	673	291	691	244
Days open	24	5	16	13	19	11	17	9
			Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**
Catch Value $(\$10^6)$			9.76	0.13	9.57	0.12	9.94	0.12
Marginal Value$(\$10^6)$			0.19		–		0.18	
NPDV $(\$10^6)$			107	3.6	111	3.4	113	3.4
Marginal Benefit $(\$10^6)$			–		4	–	2	–

Commercial Fishery C/f Standardized

	Historical		PRE		COMM		TEST	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Ret (10^3)	1561	481	1544	728	1495	714	1505	704
Cat (10^3)	754	307	664	634	675	650	692	622
Esc (10^3)	684	207	780	269	720	248	714	201
Days open	24	5	16	13	18	13	17	12
			Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**
Catch Value $(\$10^6)$			9.76	0.13	9.91	0.14	10.16	0.13
Marginal Value$(\$10^6)$			–		0.15		0.25	
NPDV $(\$10^6)$			107	3.6	111	3.7	113	3.6
Marginal Benefit $(\$10^6)$			–		4		2	

Table E8. Improved Pre-season Forecast($\sigma^2/4$). Annual results of 100 simulations of 50y duration with precision of the pre-season forecast of abundance of returns increased by factor of 4. Simulations are run with and without standardization of the commercial fishery C/f for effect of nominal fishing effort on q.

Commercial Fishery C/f Not Standardized

	Historical		PRE		COMM		TEST	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ret (10^3)	1561	481	1561	723	1434	703	1459	698
Cat (10^3)	754	307	683	634	668	555	681	557
Esc (10^3)	684	207	779	227	667	252	678	227
Days open	24	5	15	12	18	10	16	9

	PRE		COMM		TEST	
	Mean	SE	Mean	SE	Mean	SE
Catch Value ($\$10^6$)	10.04	0.13	9.82	0.12	10.01	0.12
Marginal Value ($\$10^6$)	0.03		-		0.19	
NPDV ($\$10^6$)	109	3.6	113	3.4	114	3.4
Marginal Benefit ($\$10^6$)	-		4		1	

Commercial Fishery C/f Standardized

	Historical		PRE		COMM		TEST	
Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ret (10^3)	1561	481	1561	723	1499	705	1512	700
Cat (10^3)	754	307	683	634	687	637	696	623
Esc (10^3)	684	207	779	227	712	213	716	189
Days open	24	5	15	12	17	13	16	12

	PRE		COMM		TEST	
	Mean	SE	Mean	SE	Mean	SE
Catch Value ($\$10^6$)	10.04	0.13	10.10	0.13	10.23	0.13
Marginal Value ($\$10^6$)	-		0.06		0.13	
NPDV ($\$10^6$)	109	3.6	113	3.6	114	3.6
Marginal Benefit ($\$10^6$)	-		4		1	

Table E9. Perfect Management. Annual results from 100 simulations of 50y duration where abundance of returns is known but fishery is controlled as in TEST scenario (PFOR) and where abundance of returns is known and catch in excess of escapement requirements is taken exactly (PERF). Statistics are calculated as in Tables E2 and E3.

	Historical		PFOR		PERF	
Variable	Mean	SD	Mean	SD	Mean	SD
Ret (10^3)	1561	481	1585	718	1601	718
Cat (10^3)	754	307	712	633	726	695
Esc (10^3)	684	207	772	147	775	66
Days open	24	5	14	11		
			Mean	SE	Mean	SE
Catch Value ($\$10^6$)			10.47	0.13	10.67	0.14
Marginal Value ($\$10^6$)			-		0.20	
NPDV ($\$10^6$)			113	3.6	115	3.9
Marginal Benefit ($\$10^6$)				-		2