Biology and Management

How the Biology of Pacific Whiting Might Constrain the Development and Stability of the Fishery

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INTRODUCTION

Pacific whiting, *Merluccius productus,* is currently the most abundant commercially harvested groundfish off the Pacific coast of California, Oregon, and Washington. It is a codlike species found over the continental shelf and slope from southern Baja California in Mexico to the Queen Charlotte Islands in Canada. The exploitation of the coastal stock of Pacific whiting was developed by foreign fishing fleets beginning in the mid-1960s. Through joint ventures with foreign processors and recent improvements in processing technology and innovative products, the U.S. industry is increasing its domestic exploitation of this species. This review will discuss the basic characteristics of the biology, life history, distribution, and abundance trends of Pacific whiting. Biological constraints on the development and stability of the fishery will also be discussed. Other reviews of the biology of Pacific whiting have been reported by Stauffer (1985), Bailey et al. (1982), and Francis (1983).

BIOLOGY AND LIFE HISTORY

Within its range, Pacific whiting consists of four reproductively isolated stocks. The major stock, and the one to which I will limit my remarks, is the coastal stock found off central Baja California (27°N lat.) to the Queen Charlotte Islands (52°N lat.).

Male and female Pacific whiting both mature at a length of approximately 40 cm, when they weigh about 0.4 kg (Stauffer 1985). This means that some three-year-old fish and most four-year-old fish are mature. Fecundity appears to be approximately 200 eggs per gram of female body weight (MacGregor 1966).

Pacific whiting spawn from December through April, with peak spawning occurring during January and February. Spawning takes place in the southern end of their range, between Baja California and San Francisco. Observed spawning concentrations of whiting are scattered sparsely throughout a wide expanse of ocean. Spawning occurs as far as 400km off the coast in dense, well-defined aggregations between 100 and 400 m below the surface.

Pacific whiting undertake a significant annual migration from their spawning grounds in the area between Baja California and San Francisco to their feeding grounds off Oregon, Washington, and British Columbia (Bailey et al. 1982) (figure 1). They arrive over the continental slope off the coast of Oregon and Washington by the third week in April and off Vancouver Island by late May, travelling about three to six nautical miles per day (Stauffer 1985). The fish move onto the shelf in June and remain in these feeding grounds until fall. Whiting stratify by length, age, and sex along the coast Older, larger fish migrate farther north, and females, because they grow to a larger size, dominate the earlier arrivals and more northerly residents of the summer feeding grounds. Whiting also exhibit a diurnal vertical migration, apparently in pursuit of their main prey, euphausiids. At dusk whiting ascend to the top 20 m, returning abruptly to 100-250 m at dawn.

Ages of Pacific whiting are determined from annual rings on the surfaces and cross sections of their otoliths. The surface ageing method has been found to be accurate through age 11, by which time most growth has been completed (Dark 1975; Beamish 1979). Whiting complete about 75% of their growth in length and 50% of their growth in weight by 4.5 years of age. Following maturation, females outpace males and grow to an average maximum size of 61 cm (1.3 kg) while males grow to only about 56 cm (1.0 kg) (figure 2).

Pacific whiting feed primarily on euphausiids and fish. They also eat shrimp and squid. Apparently little or no feeding takes place during their winter spawning. The diet of larger whiting includes a higher proportion of fish, including smaller whiting, sand lance, Pacific herring, and deep-sea smelt (Livingston and Bailey 1985). Within a season, whiting gain weight on the feeding grounds and lose weight during migration and spawning.
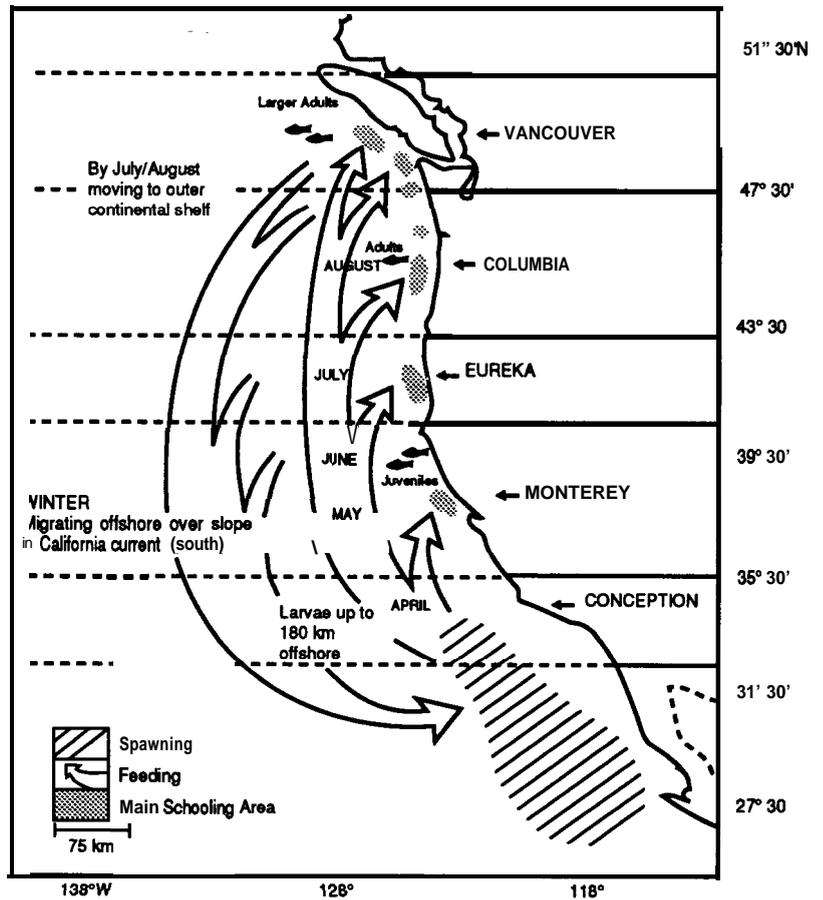
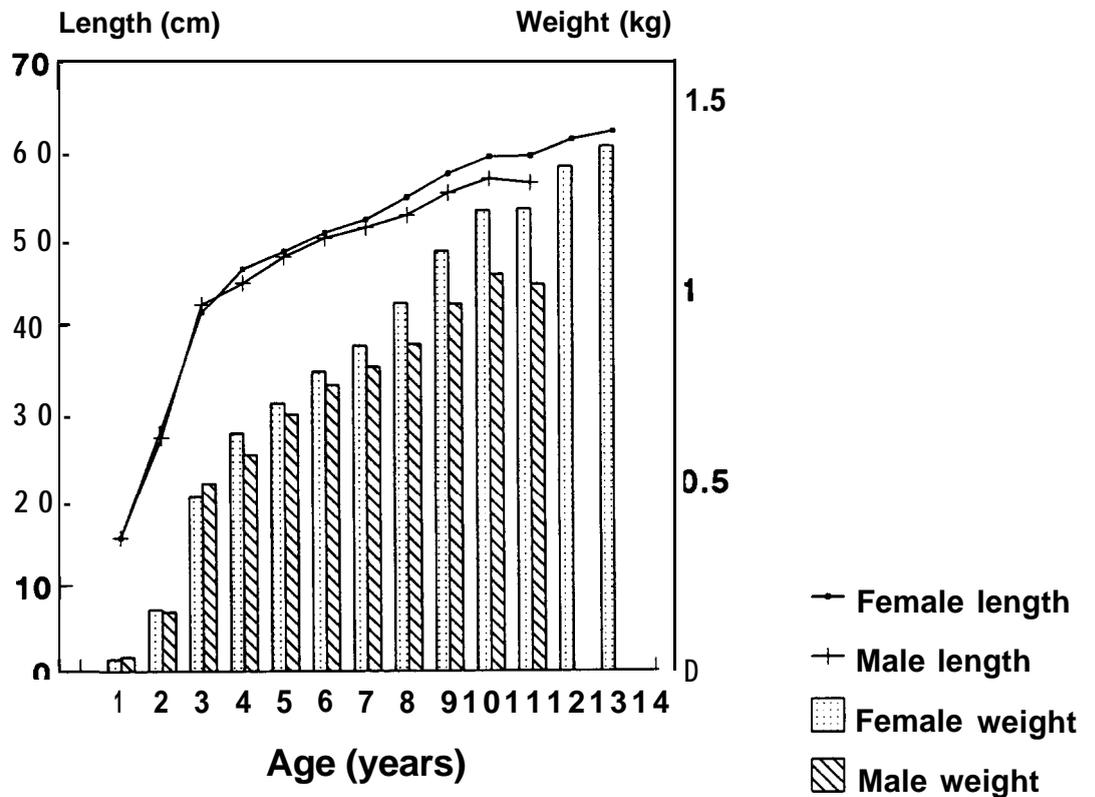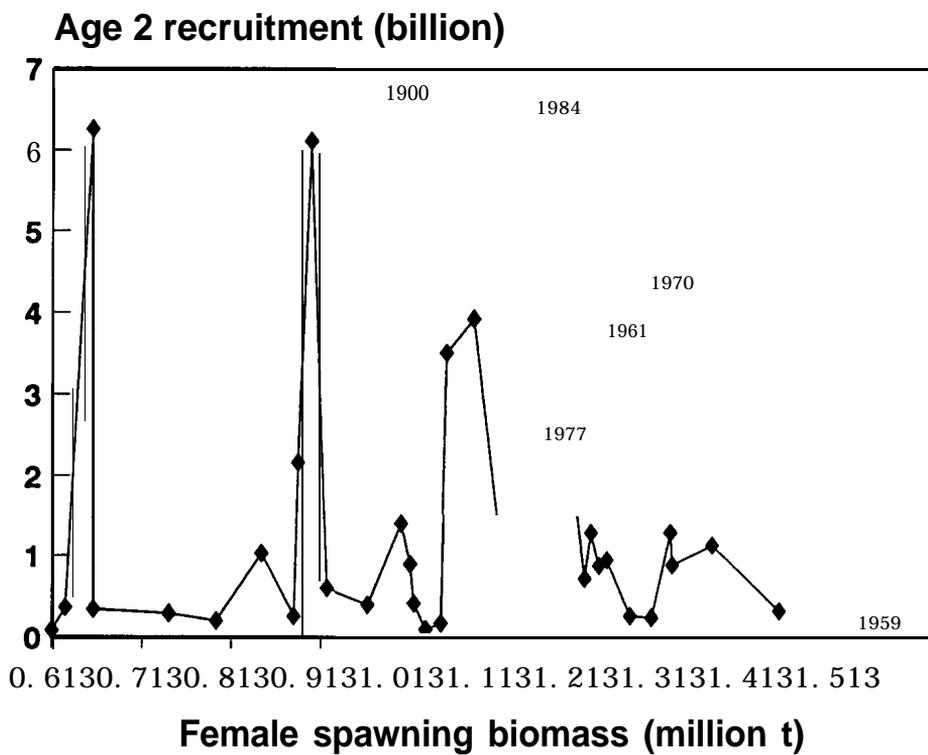*Figure* 1. *Migratory patterns* *Of Pacific whiting (from Bailey et al. 1982).*

Figure 2. Pacific whiting mean kngth and weight at age by sex.

Age 2 recruitment (billion)

Figure 3. Recruitment history of Pacific whiting, 1959-1987.

The coastal population of Pacific whiting exhibits a high rate of infection with a protozoan parasite of the phylum Myxosporea (Nelson et al. 1985). This parasite enters individual muscle fibers, forming pseudocysts. While there is no evidence that these infections cause any harm to consumers, they have a significant effect on the texture of fillets and other products from infected fish. Proteolytic enzymes are produced by the parasite as natural metabolites. While the host fish is alive, its excretory system can eliminate these chemicals. Upon capture, the enzymes accumulate in the muscle fibers and start to break down the flesh, resulting in a soft, mushy texture that is unsuitable for marketing.

Pacific whiting begin to recruit to the fishery at age three years off northern California. They are nearly completely recruited to the Oregon-Washington summer fishery by age five. The extreme recruitment variability of Pacific whiting (figure 3) has a major influence on the population dynamics of the stock. The population is typically dominated by one or two large year classes, with other year classes contributing very little to the biomass. Recent large year classes have occurred in 1973, 1977, 1980, 1984, and 1987. The occurrence of large year classes has been correlated with years of weak upwelling conditions and warm coastal surface temperatures (Bailey and Francis 1985).

One explanation is that strong upwelling pushes larval whiting offshore into a less productive habitat, reducing their survival rates.

ABUNDANCE AND STOCK ASSESSMENT

The biomass of Pacific whiting is measured every three years by NMFS with concurrent bottom trawl and echo integration (hydroacoustic) surveys, designed to assess both the demersal and midwater components of the stock. Figure 4 presents these combined estimates for the five triennial surveys. The dynamics of the population are more comprehensively modelled by including information regarding the magnitude and biological composition of the catches each year using stock synthesis (Methot 1989). The results are issued annually as a stock assessment document through the Pacific Fishery Management Council (Dorn et al. 1990; Dom and Methot 1991). The effects of variable recruitment can be seen in the history of biomass estimates. Years when only one or two strong year classes were present (1977-1983) can be contrasted with 1986, when three large year classes were present. Currently, the 1980, 1984, and 1987 year classes are supporting the fishery, but the latter one is only moderately strong.
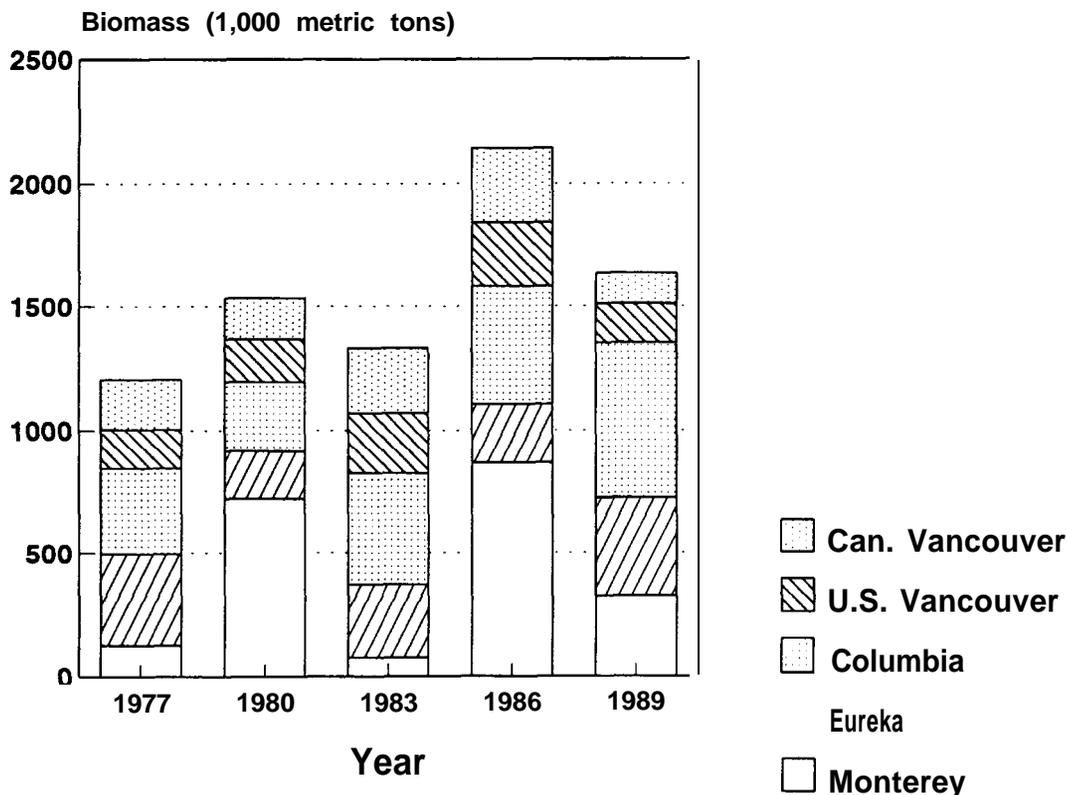
Biomass (1,000 metric tons)

Figure 4. Pacific whiting research survey biomass estimates by year and INPFC area.

Year

Legend:
- Can. Vancouver
- U.S. Vancouver
- Columbia
- Eureka
- Monterey

IMPLICATIONS FOR FISHERY DEVELOPMENT AND STABILITY

The three most critical biological characteristics, in terms of the ability of the coastal Pacific whiting population to sustain a fishery, are (1) its annual migratory pattern, (2) its high rate of parasite infection, and (3) its extreme recruitment variability. Since larger fish, and consequently females of an age class, arrive in the area of the fishery earlier than the males and stay longer before migrating back to the south, the availability of certain components of the stock vary with the timing and location of fishing. For example, a fishery occurring in the INPFC Monterey area would catch mostly immature fish. Such differential vulnerability can contribute to the instability of the population.

The marketing problems caused by the Pacific whitings parasitic infection have been an impediment to fishery development in the past, but appear to have been overcome with innovative products and processing.

The "boom or bust" nature of Pacific whiting recruitment seems to be the most difficult problem facing the development of this resource. The dependence on strong year classes for the yields from the population means that the long-term stability of the yields is always in doubt Because of a lack of strong recruitment since 1984, the current age structure of the fishable Pacific whiting population is rela-

tively old. If recruitment continues near average levels, the outlook for the immediate future is for a continuing slow decline in the annual yield. Recruitment of a strong year class would substantially increase the projected yields.

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Discussion

Q: (Barry Fisher, from the audience) Your presentation seems to indicate that the variation in the population of whiting is not exclusively due to overfishing. Has research on their cannibalistic pattern indicated anything about management methods?

A: (Wilkins) The cannibalistic nature of the fish means that a large year class will eat more members of a younger year class, making the population of the younger year class lower. The cannibalistic pattern is partly mitigated by the stratification of the species [tendency of different year classes to feed in different places], so the cannibalistic pattern is not a dominant part of their predation. Therefore, there would be no strong reason to base management strategies on this factor.

Q: Does the spawning pattern of whiting make them susceptible to fishing pressure?

A: (Wilkins) As fishing has not been permitted in the spawning areas, this hasn't been a problem.

Q: What environmental conditions favor recruitment? Do these conditions affect survival at spawning or later? Could you clarify the spawning pattern?

A: (Wilkins) Years when there are low up welling or El Niño conditions are high recruit+ ment years. These environmental conditions affect the fish at spawning. During April, spawning fish are off the Northern California shelf; they move farther north in May or June.

POTENTIAL YIELD FROM THE PACIFIC WHITING FISHERY

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INTRODUCTION

Unlike their counterparts in other scientific disciplines, fisheries scientists rarely can use controlled experiments to test hypotheses about the dynamic behavior of wild fish populations. Artificially manipulating the populations or their environment takes too long to produce results, or it is impossible, impractical, or too costly. As a consequence, fisheries scientists usually must base their conclusions and recommendations on results from experiments with theoretical models of fish populations. Although fisheries models are often viewed with skepticism by the fishing industry, the models can provide insight into the processes that control the productivity of a fish resource and they can suggest alternative strategies for harvesting that productivity.

This paper describes and examines one relatively simple model for the long-term average behavior of an idealized fish population. The model combines a traditional yield-per-recruit analysis with a spawner-recruit relationship; as a consequence, it is able to portray simultaneously the effects of short-term growth overfishing (catching fish before they have attained a favorable size) and long-term recruitment overfishing (catching fish before they have produced enough offspring). Beverton and Holt (1957) originally developed and used this model in their classic analysis of the North Sea stocks of plaice and haddock. Although it has not been widely used by fisheries scientists, this model, or variants of it, appears in Cushing (1973), Shepherd (1982), Sissenwine and Shepherd (1987), and Clark (1991).

YIELD FROM A COHORT

First consider the total weight (the biomass) of a collection of fish (a cohort), all of which were born at the same time. As time passes, two processes operate on this cohort and cause its biomass to change: some individuals die; the survivors grow and increase in size. Together these processes cause the biomass to rise to a maximum and then decline. For Pacific whiting, the age at which a cohort attains its maximum biomass is about four years. If we could harvest all the fish simultaneously, we could obtain a maximum catch by taking all the fish when they reach this critical age.

With Pacific whiting, as with most other commercially exploited species, we cannot catch all the fish simultaneously when they achieve a particular age. Instead we harvest a portion of the fish available over an interval of time. The upper panel of figure 1, for example, illustrates how fishing might affect the biomass of a cohort of Pacific whiting in which initially there are 1000 one-year-old fish (the recruits). We begin harvesting when the fish attain an age of four years, we cease fishing when they reach an age of twelve years, and at each instant of time we catch 30% of the available fish. The hatched area represents the total weight of the fish caught (the yield) during the eight-year span. In this example, we get a yield of about 186 kg. In the lower panel the fishable lifespan extends from age 3 to age 12, and the yield is about 201 kg.

The lower panel of figure 1 illustrates another phenomenon. Harvesting reduces the biomass of the mature portion of the stock (the spawning stock biomass). In this panel we begin fishing before the fish attain maturity (at age 3.5 years), and fishing reduces the biomass of the mature population to about one-third of its size in an unexploited stock. In the upper panel we begin fishing after the fish attain maturity, and our fishing reduces the spawning stock biomass to only 4.4% of the virgin level.

If we halve (or double) our rate of fishing to 15% (or 60%), the yield will not be half (or double) the values shown in the figure. Changing the rate of fishing alters the shape of the biomass curve. The greater the rate of fishing, the more rapidly the biomass declines.

The age at which we first begin capturing fish, in combination with the rate of fishing, determines how much yield we will take from a cohort and determines how many adults will be left to produce future generations.
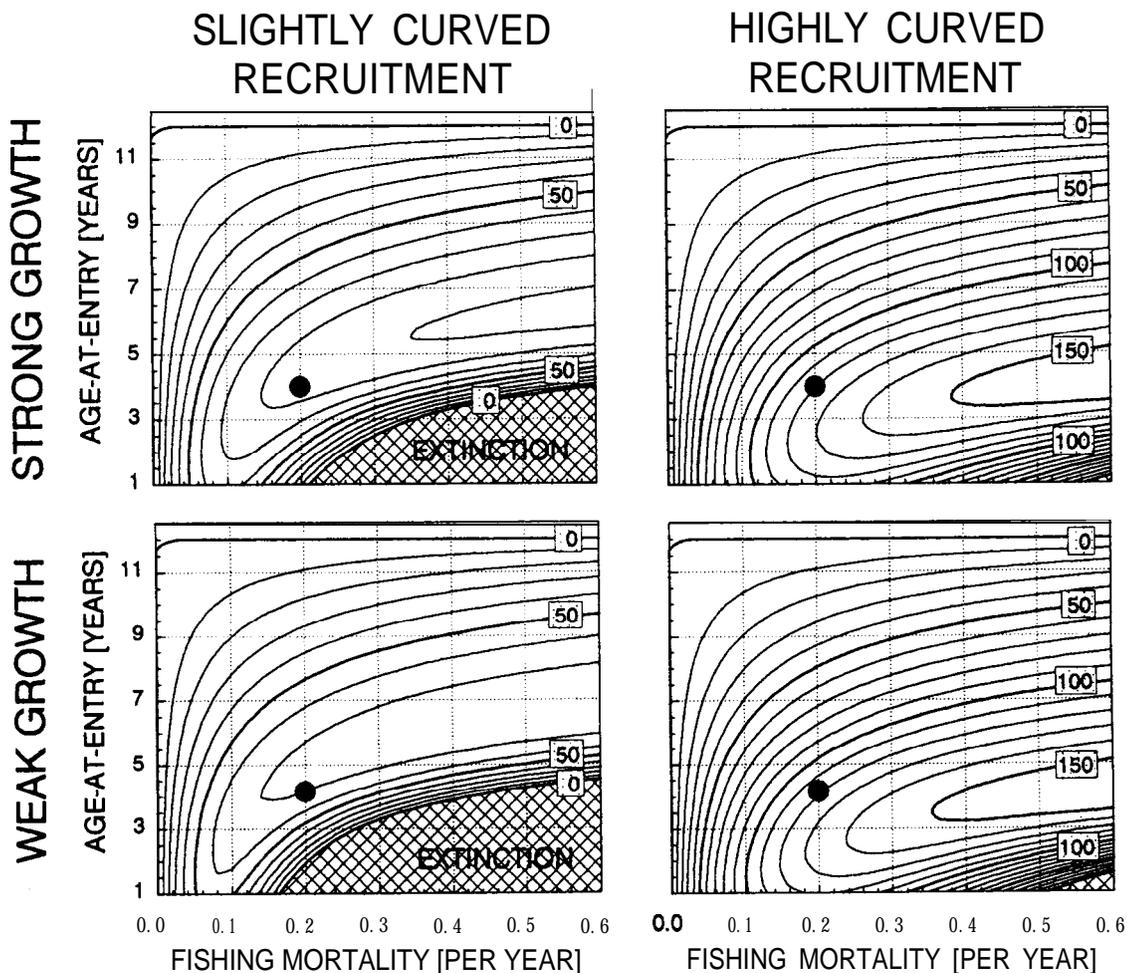
SLIGHTLY CURVED RECRUITMENT

HIGHLY CURVED RECRUITMENT

STRONG GROWTH

WEAK GROWTH

AGE-AT-ENTRY [YEARS]

FISHING MORTALITY [PER YEAR]

Figure 1: Biomass, yield, and spawning biomass from a cohort of Pacific whiting.

RECRUITMENT AND SPAWNING STOCK BIOMASS

In order to gauge how today's fishing affects the fish stock that will be available in future years, we need to relate reproduction with the subsequent recruitment of offspring. Fecundity is proportional to body weight in many species of fish, therefore it is reasonable to assume that the number of eggs produced by a cohort is roughly proportional to the cohort's total biomass over its reproductive lifespan. However, it is almost certainly unrealistic to assume that a cohort's production of offspring is proportional to the number of eggs laid by the cohort. Over the generations a strictly linear relationship between the number of eggs and the number of reproductively successful offspring would lead either to extinction or to a population that was infinitely large. The fact that fish populations remain reasonably stable over time suggests that the relationship between egg production (that is, spawning stock biomass) and recruitment is curved and that there is relatively less recruitment at high levels of egg production.

Establishing with reasonable certainty the relationship between stock **size** and recruitment is a central and unresolved problem in fisheries science. Uncontrollable environmental factors apparently have a strong effect on the relationship (for example, Hollowed and Bailey 1989). Furthermore, the high imprecision in our estimates for spawning biomass and recruitment makes the relationship **difficult** to measure. One method for dealing with our uncertainty about the stock and **recruitment** relationship is to use a range of alternatives and investigate how they **affect** the results.

SUSTAINABLE YIELD FROM PACIFIC WHITING

If we combine the relationship for the yield from a cohort with the relationship between spawning stock biomass and recruitment, we can derive a model that predicts the average yield that we can harvest annually on a sustained basis. We cannot control the biological factors-such as natural mortality, growth,
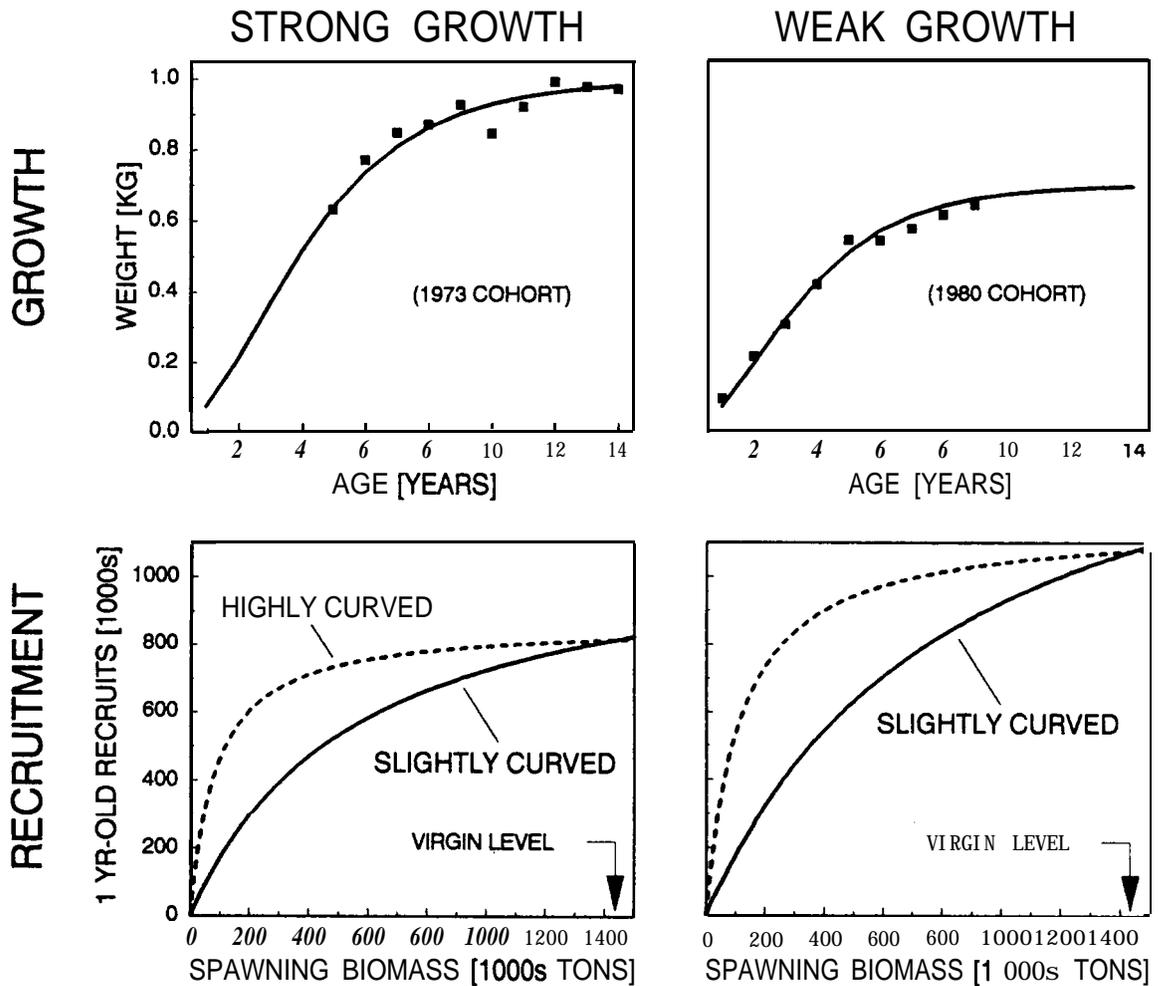
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STRONG GROWTH

WEAK GROWTH

Figure 2: The growth curves and recruitment relationships that produce the sustainable yield relationships shown in figure 3.

and the recruitment relationship—that determine the sustainable yield. However, we can manipulate the rate of fishing (the fishing mortality) and the age at which fish are first harvested (the age-at-entry). The objective in applying this type of model to the stock of Pacific whiting is to evaluate whether there are combinations of fishing mortality and age-at-entry that will produce larger yields or that will more economically produce a given yield.

Previous studies of Pacific whiting have established that cohorts born in different years sometimes follow separate growth schedules (Hollowed, Methot, and Dom 1988; Dom and Methot 1989). In order to see how differences in growth affect the potential yield of Pacific whiting, we can compare the results derived from two growth schedules, one for strong growth and one for weak growth (shown in the upper panels of figure 2).

Over the observed range of values for spawning biomass, researchers have been unable to detect any clear relationship between spawning stock biomass and recruitment (Dom et al. 1990). This may be due to the scar-

city and high degree of variability in the data. Alternatively, the absence of a pattern suggests that the relationship may be like the highly curved ones shown in the lower panels of figure 2. In those relationships there is little change in the average number of recruits produced by levels of spawning biomass greater than 500,000 metric tons. In order to see how differences in the recruitment relationship affect potential yield, we can compare the results from two sets of recruitment relationships, one that is highly curved and one that is only slightly curved (shown in the lower panels of figure 2). Different curves apply, depending on whether growth is strong or weak. In order to keep the relationships on the same relative scale, we must choose the recruitment curves so that for an unexploited stock they all produce the same spawning biomass.

Figure 3 shows how potential yield varies with fishing mortality and age-at-entry for the different combinations of growth and recruitment. The contour lines trace out the combinations of fishing mortality and age-at-entry that on average produce a particular annual yield.

The large dot on each graph represents the current position for the Pacific whiting fishery; the rate of fishing is about **20%,** and **fish** are first vulnerable to capture at about four years of age. In the hatched regions, in the lower right portion of each panel, the rate of removals by the fishery exceeds the stock's biological productivity, and extinction results.

If we compare the upper and lower panels, we can see that changes in growth do not have much effect on the sustainable yield of **Pacific** whiting. However, if we compare the panels on the left with those on the right, we can see that the amount of curvature in the recruitment relationship has a pronounced effect For example, if **growth** is strong and the recruitment relationship is only slightly curved (shown in the upper **left** panel), the current fishing strati egy **(indicated** by the large dot) produces a sustainable yield of about 84,099 metric tons per year. However, if the recruitment relationship is **highly curved** (shown in the upper right panel), the current strategy produces a sustainable yield of about 119,009 metric tons per year.

If the true relationship between spawning stock biomass and recruitment is the slightly curved one, then the current 20% rate of fishing is very near the level that produces the maximum sustainable yield for an age-at-entry of four years. We could achieve a modest increase in yield by increasing the rate of fishing to about 35% if **we** coupled this with an increase in the age-at-entry to about 5.5 years. Note that if we increase the rate of fishing without raising the age-at-entry, then the sustainable yield will decrease! If the true recruitment relationship is the highly curved one, however, then we are currently **underfishing** this stock. By doubling our rate of fishing, we could significantly increase the annual yield.

The appendix gives the full details of the parameters and equations of the model for the potential yield of **Pacific** whiting.
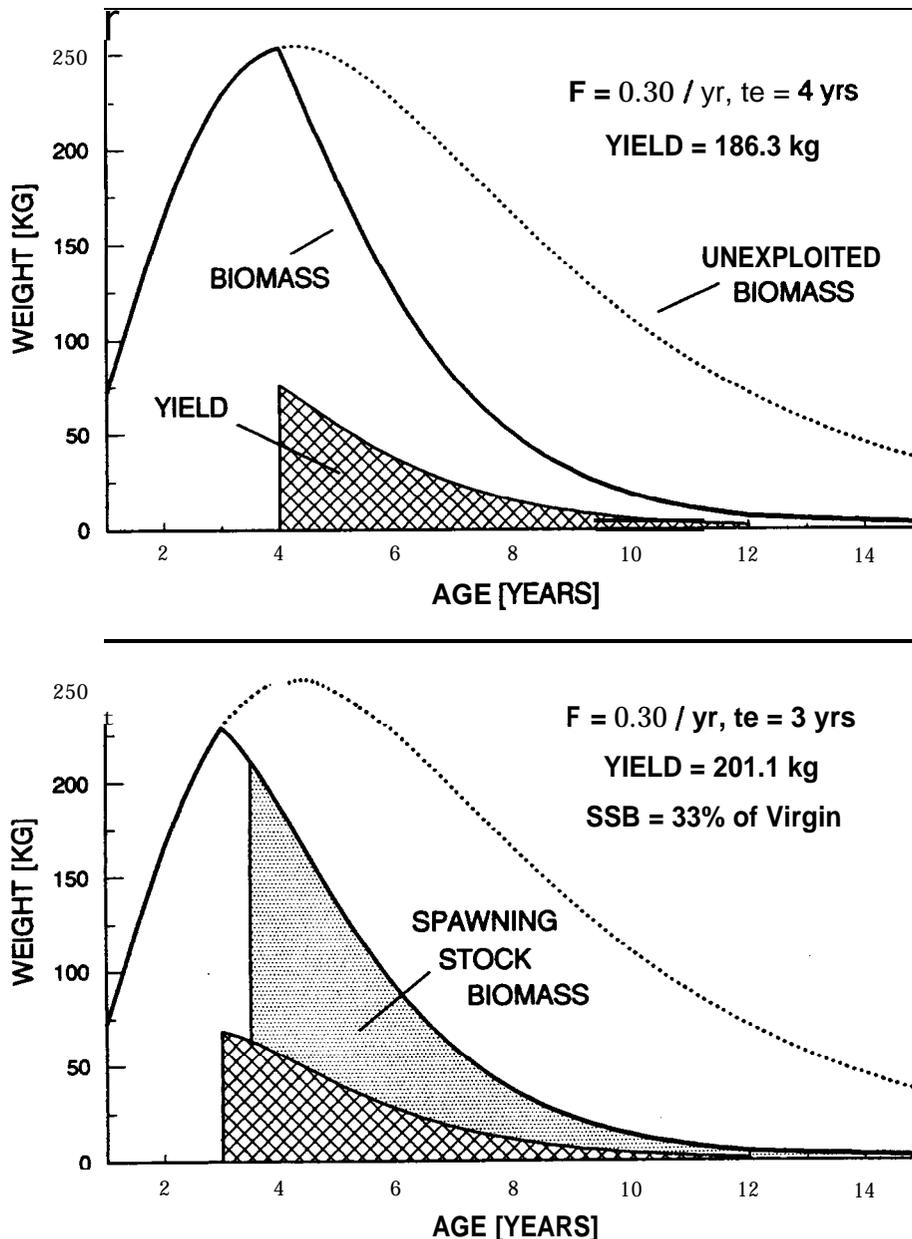

Figure 3: Contours Of sustainable yield (thousands Of metric tons per year) from a fishery for Pacific whiting.

DISCUSSION

Most fishermen and fisheries managers are familiar with the concept of maximum sustainable yield (MSY, the largest average rate of catch that can be taken on a sustained basis). However, they are probably unaware that MSY varies with the age-at-entry. For example, examine the upper left panel of figure 3. The lowest point on each contour line represents a combination of age-at-entry and fishing mortality that produces an MSY. For an age-at-entry of two years, we obtain an MSY of about 70,000 metric tons per year with a fishing mortality rate of just over 0.1 per year. If we increase the age-at-entry to 5.5 years, we can obtain an MSY of about 90,000 tons per year with a fishing mortality rate of about 0.36 per year.

Figure 3 also illustrates that we can lessen the risk of causing a year-class failure if we make the age-at-entry large enough to allow young fish to spawn. Pacific whiting reach maturity at about 3.5 years of age. If we regulate the age-at-entry in the whiting fishery to be 5 years or greater, then even extremely high rates of fishing will not reduce the spawning biomass to dangerously low levels. With Pacific whiting it should be possible to manipulate the age-at-entry with mesh-size regulations or with time and area closures.

The greatest uncertainty about how much Pacific whiting we can take on a sustained basis lies in the shape of the recruitment relationship. If we gamble that the relationship is highly curved and then increase the rate of fishing, we will attain higher yields if we are correct and lower yields if we are wrong. With our current policy and its conservative fishing rate, it will take a very long time to collect enough information to establish the recruitment relationship. Perhaps we should adopt a policy of deliberate overfishing for a few years so that we can determine more accurately the shape of the recruitment relationship.

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APPENDIX: The Equations of the Model for Whiting Yield

In the following equations the variable t denotes age in years.

GROWTH: $$W(t) = W_\infty \cdot [1 - e^{-k \cdot (t-t_0)}]^3$$

        W   is the average weight-at-age of a fish.

	W_∞	k	t_0
Strong Growth	1.0 kg	0.36 /yr	-0.5 yr
Weak Growth	0.70 kg	0.42 /yr	-0.5 yr

SURVIVAL: $$N = N(t, F, t_e)$$

$$N = \begin{cases} R \cdot e^{-M \cdot (t-t_r)} & \dots\ t \le t_e \\[2ex] R \cdot e^{-M \cdot (t_e-t_r)} \cdot e^{-(F+M) \cdot (t-t_e)} & \dots\ t_e < t \le T \\[2ex] R \cdot e^{-M \cdot (t_e-t_r)} \cdot e^{-(F+M) \cdot (T-t_e)} \cdot e^{-M \cdot (t-T)} & \dots\ T < t \end{cases}$$

    N   is the number of living fish.
    R   is the number of one-year-old recruits.
    t_r is the age at recruitment: t_r = 1 year.
    t_e is the age at entry to the fishery.
    T   is the age at which fish cease to be vulnerable to fishing; T = 12 years.
    M   is the instantaneous rate of natural mortality: M = 0.237 per year.
    F   is the instantaneous rate of fishing mortality.

BIOMASS: $$B(t) = W(t) \cdot N(t, F, t_e)$$

    W   is the total weight of the surviving fish.

YIELD: $$Y(F, t_e) = \int_{t_e}^{T} F \cdot N(\tau, F, t_e) \cdot W(\tau)\ d\tau$$

    Y   is the total weight fish caught over the fishable lifespan from age t_e to age T.

SPAWNING STOCK BIOMASS: $$SSB(F, t_e) = \int_{t_R}^{\infty} N(\tau, F, t_e) \cdot W(\tau)\ d\tau$$

    SSB   is the total weight of fish over the reproductive lifespan from age t_R to final senescence.

RECRUITMENT: $$R(F, t_e) = \frac{SSB(F, t_e)}{1 - a \cdot [1 - SSB(F, t_e)/\beta]}$$

    R   is the number of one-year-old recruits produced by the given spawning stock biomass (SSB).

		Strong Growth	Weak Growth
Slightly Curved	α	0.5	0.5
	β	567,720 mt	856,420 mt
Highly Curved	α	0.9	0.9
	β	776,610 mt	1,244,090 mt

All four recruitment relationships produce 1.438 million metric tons of unexploited spawning stock biomass (Fig.2).

EQUILIBRIUM SPAWNING BIOMASS:

$$SSBeq(F,te) = (\beta/\alpha) \cdot [\ SSB(F,te)/R - 1 + a\ ]$$

SSBeq is the long-run average spawning stock biomass. SSB/R is the short-run spawning biomass per recruit.

EQUILIBRIUM RECRUITMENT:

$$Req(F,te) = SSBeq(F,te) / [\ SSB(F,te)/R\ ]$$

Req is the long-run average one-year-old recruitment.

EQUILIBRIUM YIELD:

$$Yeq(F,te) = Req(F,te) \cdot [\ Y(F,te)/R\ ]$$

Yeq is the long-run average weight of fish caught from a cohort over its fishable lifespan. Y/R is the short-run yield per recruit.

Discussion

Q: How does it **affect** your predictions if we don't really know what foreign vessels are catching in our waters?

A: (Sampson) This wouldn't affect these models because the models consider total catches, including foreign ones.

Q: (Barry Fisher, from the audience) The data we used to get from the observer program on the foreign fishing fleet could have been useful. Why don't we use the fishing fleet to gather more data if it could improve the projections used for management of stocks?

A: Sampson answered that what we need to be able to do is to predict environmental changes like El **Niño,** but this ability seems unlikely. The session leader interjected that what the questioner was implying is that we need to improve our projections with better data, such as weather cycle data, to improve management decisions. Fisher added that looking at one species alone is a mistake; we need to examine the interactions in a multispecies fishery, as part of the overall ecology.

Q: What about the economics of this situation? How do you include supply and demand in the model?

A: (Sampson) These factors can be included. To do so, we need to attach likelihoods to each recruitment scenario, then do the economic analysis based on the situation we think is most likely to occur.

Several additional comments were made in summing up. Mark Wilkins commented on the idea of trying to **analyze** the whole system rather than one species alone; this is already happening up in Alaska and they have fallen behind down here. Fisher added from the audience that the scientists need to let the industry help them where possible, both in gathering data and in raising funds to support the research.

A Multiple-Objective Bioeconomic Policy Model of the Pacific Whiting (*MERLUCCIUS PRODUCTUS*) Fishery

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INTRODUCTION

Modern fishery management embraces a broad range of biological, economic, and social objectives (benefits). The emergence of the concept of optimum yield as the legislative principle of fisheries management in the United States explicitly recognizes the multiple-objective nature of fishery management (Healey 1984). The fundamental problem with multiple-objective management, however, is the need to reconcile conflicting objectives. Bailey and Jentoft (1990) point out the necessity of making difficult choices among policy objectives in fishery management.

Traditionally, the analysis of fishery policy has centered on single objectives. For example, much of the analysis has focused on the issue of biological conservation. Although this focus has been essential for maintaining the long-term productivity of the resources, as mandated by the Magnuson Fishery Management and Conservation Act (MFMCA), it has neglected the economic and social aspects of the fishery. In contrast, economists have tended to favor traditional cost-benefit analysis, which focuses on the single objective of maximixing the present value of net revenues. Although this approach provides valuable insight, it does not fully account for the effects of policy regulations on other objectives, such as regional employment and income.

Economic analysis based on a single objective is not consistent with the nature of the political process in fisheries management, nor does it comply with the MFMCA, which mandates an integrated consideration of biological, social, and economic objectives. To overcome these problems, Cohon (1978) has suggested a modified and refined methodology for the analysis of multiple-objective decision problems. This methodology is known as multiple-objective programming, a branch of operations research that allows the consideration of multiple objectives explicitly and simultaneously.

The purpose of this paper is to summarize the recent developments of a multiple-objective bioeconomic policy model of the Pacific whiting (*Merluccius productus*) fishery. This model integrates biological, marketing, and industrial data with economic impact and regulatory policies. In particular it draws heavily from Pacific whiting stock assessments, especially the results of the stock synthesis model by Dorn and Method (1991 and 1989), Dorn et al. (1990), Method (1989), and Hollowed et al. (1987). The study also draws from several other sources, including a market survey by Sylvia and Peters (1991). To illustrate the potential use of the model, we present the results from one application and briefly discuss them.

CONCEPT, SCOPE, AND LIMITATIONS OF MULTIPLE-OBJECTIVE MODELS

Traditional (single-objective) methods of fishery policy analysis are designed to search for policy regulations that will potentially yield the highest value for the objective under consideration. In contrast, multiple-objective analysis recognizes that since fishery policy consists of noncomplementary objectives, a solution that simultaneously maximizes all the objectives does not exist. That is, a management strategy that maximizes one objective does not necessarily maximize the other objectives. Multiple-objective models attempt to identify policy alternatives representing full utilization[1] of the resource. A policy alternative represents full utilization if, given the objectives, the time horizon, and the constraints, there is no other possible alternative that will produce an increase in one objective without causing a degradation in at least one other objective. Since there are many objectives, and

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[1]These solutions are called, alternatively, nondominated, noninferior, or Pareto efficient.

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many ways to value these objectives, there may also be many possible ways to fully utilize the resource. The principal characteristic of full utilization alternatives is that, in moving from one alternative to another, we must trade-off the objectives. It must be emphasized that full utilization refers to all of the objectives selected for the analysis. Multiple-objective analysis systematically identifies full utilization alternatives and the trade-offs implied by the selection of these alternatives.

The principal disadvantages of multiple-objective analysis are the large information requirements and the high computational cost, which increase exponentially with the number of objectives under consideration (Willis and Perlack 1980). As the number of objectives included in the analysis increases, the number and complexity of the solutions also increase, making the policy information more difficult to be evaluated.

Multiple-objective models, as with other kinds of mathematical models, are useful only if their limitations are clearly understood by analysts and decision makers. The essence of mathematical modelling is abstraction; therefore, models provide only a limited view of real systems. Given the complexity and uncertainty involved in fishery management, the numerical solutions of mathematical models must be interpreted with caution. Nevertheless, multiple-objective models, if used in combination with other sources of information, including the experience of the policymakers and "common sense," can be valuable tools for the decision-making process.

AN EXAMPLE: GEOGRAPHICAL DISTRIBUTION OF EFFORT

The Policy Problem

Pacific whiting exhibit an extensive northerly migration to summer feeding grounds off the coasts of Northern California, Oregon, Washington, and British Columbia (Bailey 1981). The extent of the annual migration is age and size dependent. Older fish and larger fish within a given age class tend to migrate farther north. Because the behavior and success of the Pacific whiting fishery depend on the migratory behavior of the species, geographical shifts of effort can not only complicate stock assessment, but can affect long-term yields (Dorn et al. 1990) and therefore the levels of other policy objectives.

Dom (1990), using catch and observer data from the period 19781988, identifies three areas of high Pacific whiting catches in the U.S. zone: (1) the Eureka and Monterey regions (EUR), consisting of the area south of latitude 43°00' N; (2) the area from latitude 43°00' N to latitude 46°45' N, corresponding to the southern part of the Columbia region (SCOL); and (3) the area north of latitude 46°45' N to the U.S.-Canada border, consisting of the northern part of the Columbia region and the U.S. portion of the Vancouver region (VCN). Because of their migratory behavior, Pacific whiting harvested from the different areas have different age, sex, sexual maturity and weight-at-age compositions, with the northernmost regions having, on average, larger, and older fish. In addition, because of their larger size, fishes from the northernmost regions have, depending on product form, potentially higher value per unit weight (Sylvia and Peters 1991). The northernmost regions are also likely to have a higher proportion of sexually mature females.

The following policy problem considers a situation where the Pacific whiting fishery in the U.S. is divided, for management purposes, into three subfisheries according to the regional classification described in the last paragraph. The main purpose of this exercise was to analyze the effects of regional distribution of effort on the level of benefits.

The Policy Objectives

Consider a policy decision problem where the objectives of management are the revenues[2] accruing from each of the three regions (subfisheries). In addition to revenues, maintaining the long-term productivity of the resource is also considered an objective of management. This policy problem, therefore, consists of four conflicting objectives. The policy instruments (or decision variables) for this problem are the harvests allowed from each subfishery.

Methodology, Model Structure, and Assumptions

A dynamic (time-dependent), multiple-objective mathematical program was used to analyze the policy problem just described.[3] The biological dynamics of Pacific whiting were

With the additional assumption that costs are independent of the geographical pattern of effort, gross revenues approximate changes in fishery rent.

[3] For a full description of the model, see Enriquez, unpublished manuscript.

simulated by a generalized age-structured submodel, with an exponential (Baranov) catch equation accounting for the effect of the fishery on the stock. The model divided the fishery into four subfisheries: three in the U.S. zone (as described above) plus the Canadian fishery. The Canadian fishery in this version of the model was treated as an external variable. For a detailed description of the model see Enriquez (unpublished manuscript).

The procedure used to find full utilization solutions consists of the following steps:' (1) Assign a set of arbitrary weights (that is, relative values) to the various policy objectives; (2) search for the geographical pattern of fishing yielding the maximum level of benefits given the weights assigned; and (3) repeat steps (1) and (2) for different sets of weights. The solution of each of these parameterizations represents a full utilization solution.

Because of the high computational cost, the large number of possible full utilization solutions, and the limited scope of this work, we restricted ourselves to the identification and discussion of only three solutions. For the sake of simplicity, the biological objective (that is, securing the long-term productivity of the resource) was incorporated into the model as a constraint. The spawning biomass was not allowed to fall below the cautionary level of 457 thousand tons (the biological objective was not subject to weighing.)

The analysis considered a 20-year time horizon and used the parameters estimated by the stock synthesis for the 1991 assessment of the Pacific Coast groundfish fishery (Dom and Method 1991; in particular, see tables 10 and 11). The model assumed a 3.5 oz (.1 kg) average individual fish weight difference between the southernmost and northernmost segments of the U.S. fishery. This estimate was based on the 1990 Pacific whiting stock assessment report (Dorn et al. 1990). Each solution was the result of 25 replicate runs each with a randomly generated 20-year time series of recruitment.[5] To keep catches within observed levels, we restricted fishing mortalities in the U.S. subfisheries (F_{US}) to an average of no more than $F_{US} = 1/2$.

We considered two product forms in the analysis--fillets and surimi. Total fishery pro-

duction was considered too small to affect the level of prices in the market. However, the model considered price variations for fillets, according to product size and supply availability, given by

PRICE ($/LB) = -.71 + .0095 FILLET SIZE (OZ)

This relationship was obtained from a market survey by Sylvia and Peters (1991). The price of surimi was considered constant at $1.28 per lb. The simulation used a 0.25 recovery rate for fillets and a 0.14 recovery rate for surimi.

Three solutions representing full utilization alternatives were generated. In the first solution called, Option 1, a high relative weight (see table 1) was assigned to the EUR region. This was done to force the model to concentrate effort in the southern region. In the second solution, Option 2, all the three regions in the U.S. received similar weights so as to distribute harvest throughout the three U.S. regions. In the third alternative, Option 3, a high relative weight was assigned to the northern (VNC) portion of the fishery. In all runs, the Canadian fishing mortality (F_{CAN}) was fixed (at $F_{CAN} = 0.15$). The results of the analysis are shown in table 1.

The policy options shown in table 1 represent three different ways of using the resource to its full capacity given the objectives, constraints, and time horizon considered in the analysis. Basing the results only on the levels of revenue shown in the table (and displayed graphically in figure 1), we could not prove that any one solution was absolutely superior to the others. That is, none of these solutions provides more revenues from every subfishery. For instance, Option 1 provides the highest level of revenue from the EUR region but no revenues from either the SCOL or VNC regions. Option 2 gives more revenues from the SCOL and VNC regions than Option 1 but provides $231.6 million less of discounted revenues from the EUR region. Similarly, Option 3 provides more revenues from the VNC region but very low levels from the other two regions. These results show the nature of the trade-offs involved in fishery decision making: increased benefits from one region can come only at the expense of other regions.

A typical multiple-objective problem has many full utilization solutions, all of which are equally desirable from the standpoint of multiple-objective analysis. However, only one alternative can be actually implemented. A deci-

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[4]This procedure is known as the weighing method for generating noninferior solutions (see Cohon 1978).

Variability in recruitment was simulated by randomly selecting with replacement from the time series of recruitment for the period 1958 to 1989 (see table 18 in Dom et al. 1990).

	Option 1			Option 2			Option 3		
	EUR	SCOL	VNC	EUR	SCOL	VNC	EUR	SCOL	VNC
Weights	90%	5%	5%	32%	36%	32%	5%	5%	90%
PV Revenues	726	0	0	494	147	277	14	0	722
St. Dev.	400	-		220	20	61	14	-	178
Catches	2967	0	0	1999	546	1005	76	0	2803
St. Dev.	1289	-		783	12	170	94	-	540

Revenues for each option represent the average (mean) over the 25 replicate runs and are discounted to the initial period using a 5% interest rate. Catches (totaled for the 20-year period) represent averages over the 25 replicate runs and are measured in nominal weight. Revenues are in millions of dollars and catches are in thousand tons. All figures are rounded to the nearest unit.

Table 1. Results of the multiobjective analysis as described in the text

sion has to be made as to which full utilization solution is best for the region or nation. In the multiple-objective approach used hero, such decisions are not incorporated as part of the model, but are left entirely to the decision makers.

Comparing Policy Alternatives

In principle, full utilization solutions can be compared only by introducing value judgments regarding the social importance of the objectives. Although these value judgments should be left to the decision makers, the analysts can still play a role in the process. One thing the
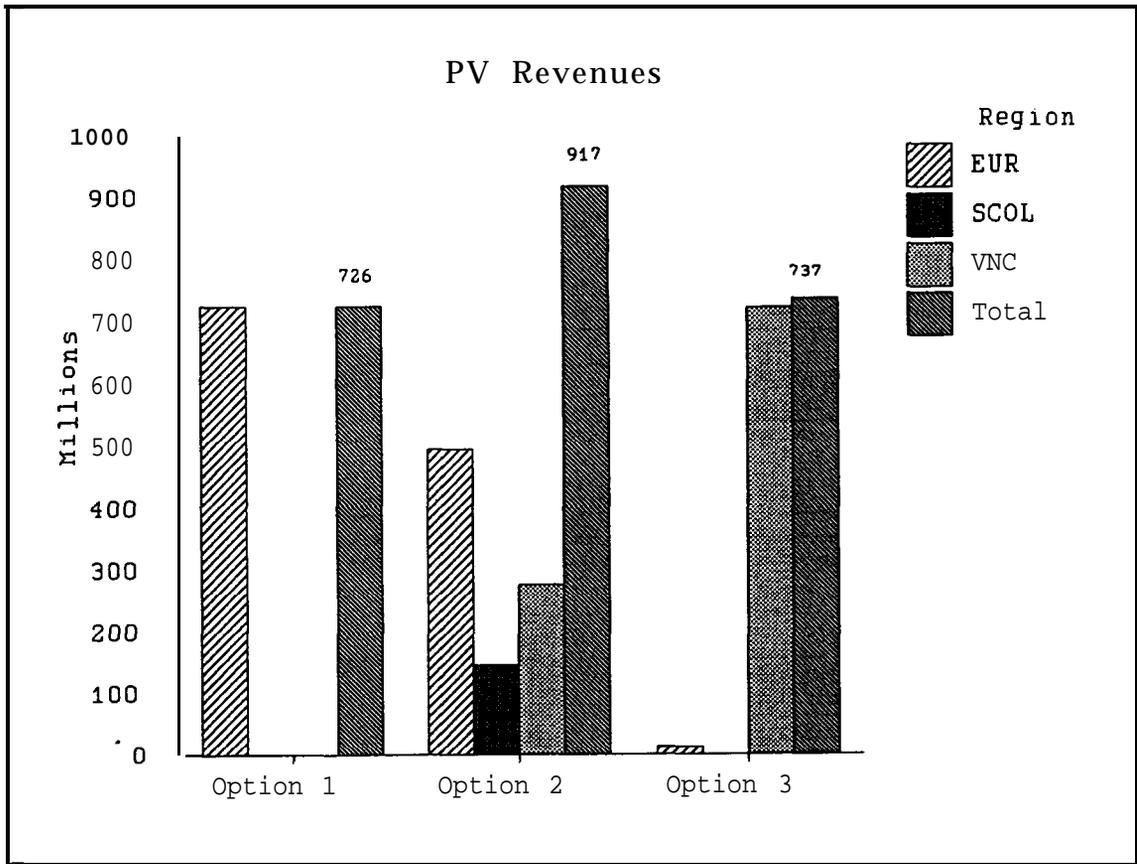

Figure 1. Discounted revenues fir the three full utilization solutions as described in the text.

analyst can do is to provide additional criteria for evaluating policy alternatives. These criteria can take many forms; for our example we use aggregate revenues and variability.

Figure 1 shows aggregate levels of (discounted) revenues across subfisheries for each option. Aggregated revenues from the fishery are potentially larger in Option 2, that is, when the effects of the fishery are spread out geographically. Option 1 is the alternative that provides fewer overall revenues because it takes a larger proportion of smaller, less valuable fishes (see figure 2). When effort is concentrated in the northern region (Option 3), catches are likely to consist of larger fishes (figure 2). However, catches from this region probably also will have a higher proportion of mature females. This is likely to affect negatively the level of spawning biomass. To avoid this effect, the model, by constraining the level of spawning biomass, restricts the levels of catches allowed from the northern portion of the fishery. This, added to the effects of natural mortality, explains the lower level of revenues from Option 3 relative to Option 2.

Variability of discounted revenues is another attribute that can be used as a criterion for evaluation. Figure 2 shows the coefficient of variation associated with discounted revenues and yield for the three policy options. The coefficient of variation measures the variability in potential revenues and can be used as a crude measure of economic risk. Option 1 has the highest level of variability of the options considered. This is because catches in the southern subfishery have a larger proportion of recently recruited individuals. Therefore, yields from this area are more directly affected by variability in year-class strength. As expected, Option 3 possesses the lowest level of variability.

An interesting aspect that surfaced from this analysis is the fact that yields from the Pacific whiting fishery are less variable than the level of discounted revenues. The reason for this is that the timing of strong year classes (that is, whether they occur earlier or later in the period of analysis) affects the discounted level of revenues. Therefore variability in revenues can be expected to increase as the rate of
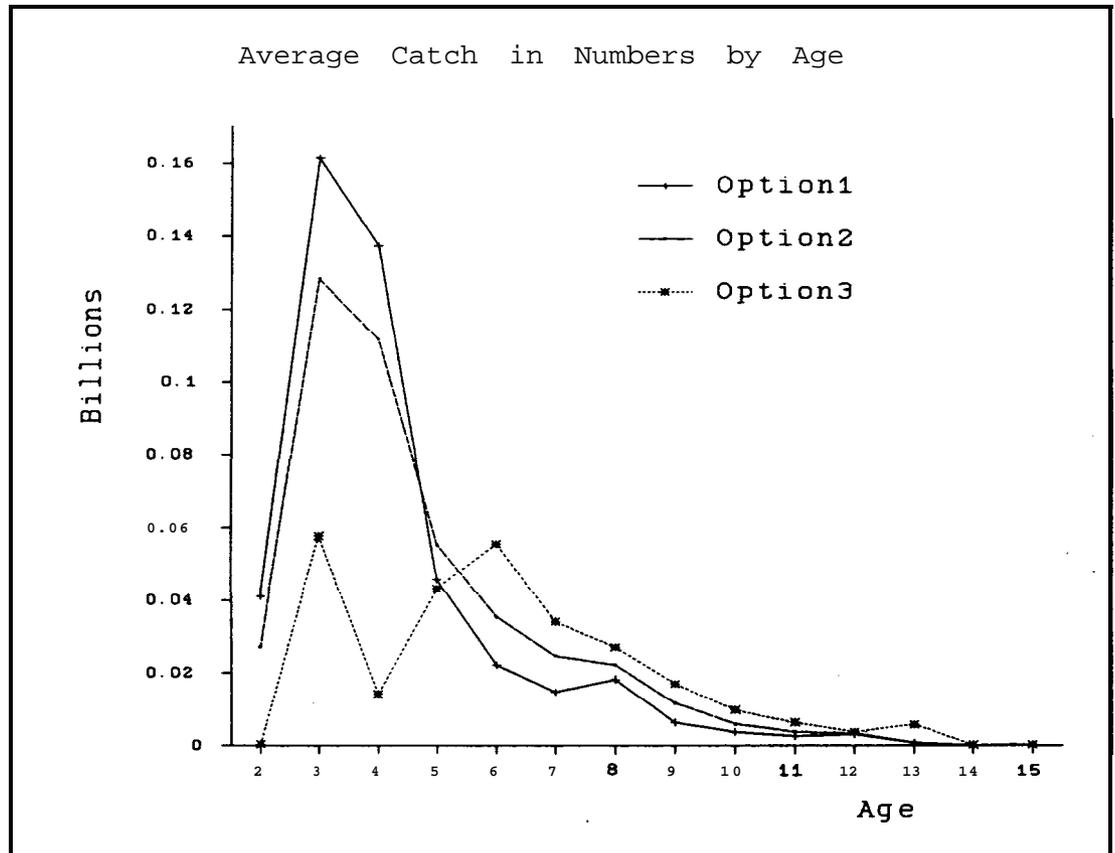

Figure 2. Average catch in numbers for the three full utilization solutions described in the text.

*The standard deviation as a proportion of mean.
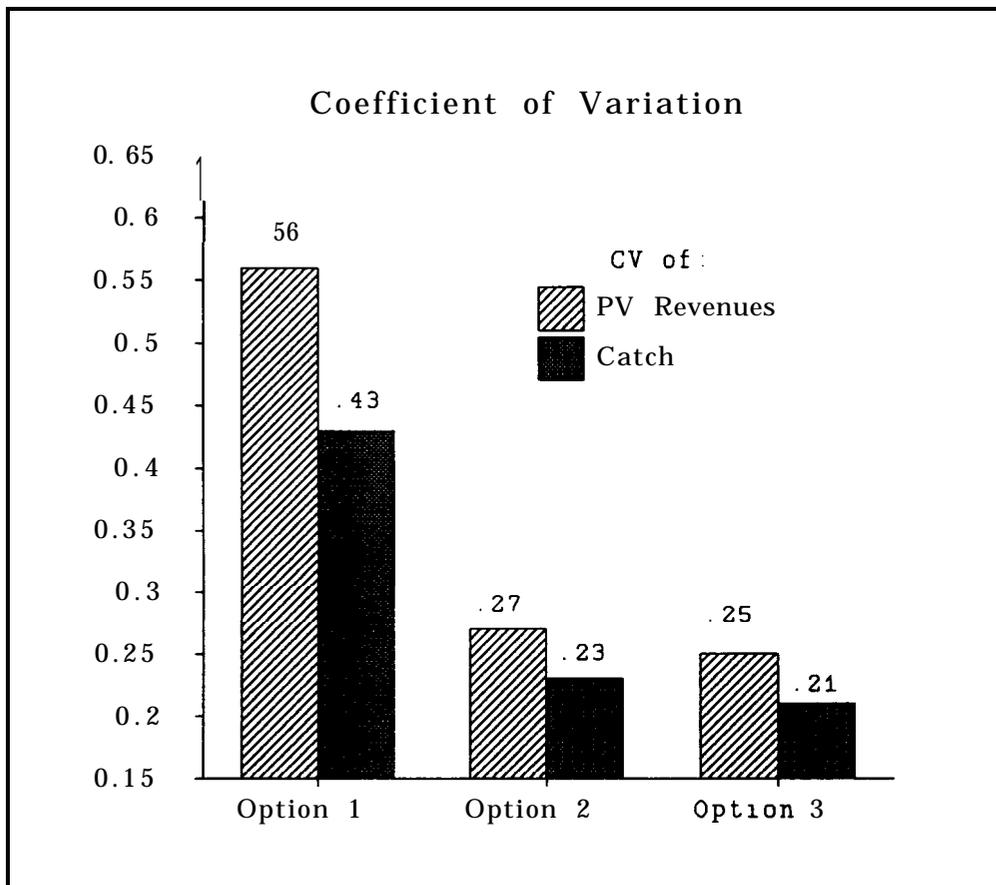
Coefficient of Variation

Figure 3. *Coefficient of variation of discounted revenues and yield for the three full utilization solutions described in the text.*

discounting is increased. In contrast, the level of yield is less dependent on the timing of strong year classes.

The policy options presented here are but three of many full utilization possibilities. Yet, the comparison suggests that the geographical distribution of **effort** could have important effects on the level of benefits expected from the fishery. Future research using multiple-objective programming techniques will address a wider range of issues affecting the Pacific whiting fishery, including onshore and offshore processing, seasonal shifts in **effort,** community impact, and assessment of biological and economic risk.

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Discussion

Q: (**Barry** Fisher, from the audience) **If** you stretch the fishery out (lengthen the time over which the fish are caught), will this result in an increase in the number of product forms?

A: (Enriquez) Yes, because then larger fish will be caught on average, and we assume larger fish give more product form options.

Q: (Fisher) Does this mean that an **"olympic"** fishery (one where all the fish is caught in a very short period of time) will actually provide less revenue?

A: (Enriquez) My analysis was not intended to address this question specifically, but it does indicate this result, since an earlier fishery will be further south and take smaller fish.

Q: (Fisher) Later in the season, more females are caught. Is this fact accounted for in your model?

A: (Enriquez) Yes, it is implicitly included in the spawning and biomass variables. What is missing so far is a consideration of how different costs are **affected;** that is being done now.

Q: When you talk about spreading out the fishery, are you talking about spreading it out over time or area?

A: (Enriquez) Both.

Gil Sylvia **interjected** here that this model provides information which can be used for management by making assumptions about demand for various product forms with different product quality characteristics. When combined with the information from the marketing study done by Sylvia and others, price effects can be included, and the researchers will be able to draw conclusions on how regulatory systems affect price. The concept of inventorying the fish in the ocean, that is, letting fish grow in the ocean rather than paying to freeze it, is among the many reasons for spreading out the fishing season over time. One extension of this analysis would be to look at the change in risk of a lower female biomass, vs. the change in risk to fishermen, of different management systems.

Q: (Steven Freese, from the audience) **The** management councils will be looking at **longer**-term models; what kind of long-term data and information will be needed to improve this model for use by the councils?

A: (Enriquez) The cost information needs to be included in the model.

Sylvia added that this approach allows you to test different economic scenarios using sensitivity analysis. You need to limit the sensitivity analysis to a reasonable range of assumptions about what is most likely. The data requirements increase exponentially as more factors are included in the analysis.

PANEL DISCUSSION ON BIOLOGY AND MANAGEMENT OF PACIFIC WHITING

Session leader: Neal *Coenen.* Panel members: *Mark Wilkins, David Sampson, Roberto Enriquez.*

Q: (Session leader) What about the use of interdisciplinary teams to provide information for management of this species, given the special economic and biological difficulties involved?

A: Each panel member responded separately to this question. David Sampson replied that using interdisciplinary approaches is a good idea, as many of the problems have both economic and biological aspects. Mark Wilkins mentioned that this type of analysis is beginning to happen, but needs to be emphasized more. Barry Fisher, from the audience, interjected that it is important to use English rather than technical jargon to communicate. Gil Sylvia remarked that Pacific whiting is a classic case where an interdisciplinary approach is needed; NMFS's approach to the problem has used different disciplines sequentially, but not together. Steven Freese of NMFS responded that the system stretches too few people in too many directions; tasks need to be more limited. Fisher praised the scientists who have had the courage to insist that an interdisciplinary approach is needed, and to criticize the council's approach, which tends to say "Let's hear from the biologists" and then, "Let's hear from the economists." As long as people are stretched too thin, management problems will continue.

Joe Easley, of the Otter Trawl Commission, commented that it would be a mistake to look at whiting in isolation; we need to examine the whole trawl fishery, which is economically, socially, and biologically integrated.

Q: (Session leader) What kinds of regulations are consistent with decreasing risk?

A: Each panel member responded separately to this question. Sampson responded that the recommended mesh size of three inches should be checked and re-analyzed, as this was only an estimate when it was originally set.. Fisher remarked from the audience that this is not enough; we need to look at double bags, chafers, and knotless Kevlan net, which would provide better escapement. Wilkins added that a prohibition against fishing in the southern areas or the use of other seasonal or area exclusions could be as effective as regulating mesh size.

Easley, from the audience, commented that the management issues between the U.S. and Canada need to be settled. Sampson added that science says we shouldn't focus on Canadian fish, as they are older year classes, and the Canadians claim that we in the U.S. underestimate the biomass. Wilkins responded that we are now beginning to work out our scientific differences with the Canadians.

We must get a handle on the catch by at-sea processors, because the current measure is not reliable, Fisher added. Easley then commented that many of the council's management problems rest in Washington, D.C. It seems as though many issues work their way up through the system and then get stuck somewhere in Washington, D.C. As a result, they never get resolved.

CLOSING REMARKS

Barry Fisher
Commercial Fisherman

Summarized by Ann L. Shriver
International Institute of Fisheries Economics and Trade

We have been exposed to a great deal of information over the last two days, all of which helps us answer the question, What do we need to do to help to develop the whiting fishery? Among the important conclusions that we can draw are the following:

• Quality assurance is crucial to developing markets for this product Organization is necessary in the industry to accomplish this, as well as to work on related issues, such as marketing and establishing quality standards or guidelines.

• There is a need to improve communication within the industry. Fishermen and processors need to communicate with each other, the rest of the industry, and the markets. Some suggestions to improve communication that have come out of this conference include the establishment of an industry newsletter, which the Astoria Seafood Laboratory has agreed to undertake, and holding more meetings like this one, in future focussing more on buyers. Government bodies and fishery managers need to be drawn into these activities.

• Continuation of the work done by the Astoria Seafood Laboratory and OSU in food technology, and in the marine resource economics research done at the Coastal Oregon Marine Experiment Station, is imperative.

• We can and should focus on the advantages of Oregon in our marketing and development efforts. Because we live in a small state, we have the luxury of knowing one another, as people in larger states such as New York and California do not. We have the Oregon Department of Agriculture, Oregon State University, Oregon Sea Grant, the Coastal Oregon Marine Experiment Station, and the Seafood Laboratory, which can all provide useful input. The Oregon Department of Fisheries and Wildlife has a much more practical, cooperative attitude than do similar departments in Alaska and Washington, and we should be able to work with them too.

• It has been suggested that we should form some sort of a whiting group. We need an industry grouping of processors and fishermen, with liaison to the Oregon Coastal Management Association, the Coastal Oregon Marine Experiment Station, and the Oregon Department of Agriculture.

• My advice to fishermen: Get out and find out more about your product and its international markets. For example, you might subscribe to *INFOFISH,* a publication described by Mr. Kano. Continue to be politically astute and kick in financial support when needed. We need to change our attitude and accept the kinds of changes in gear and handling procedures mandated by the market. We can no longer say, 'That's the way my grandfather did it and it's good enough for me."