CAN WE STABILIZE FISHERIES'BENEFITS FROM A FLUCTUATING STOCK?
A Bioeconomic Assessment of the Pacific Whiting Fishery

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ABSTRACT

Pacific whiting (*Merluccius productus)*, a commercially valuable fish species in the Pacific coast groundfish fishery, experiences extreme variability in annual recruitment. This variability causes fluctuations in stock abundance and subsequent catch and economic benefits. This study develops a stochastic bioeconomic model of the Pacific whiting fishery in order to assess various fishing strategies based upon economic and biological criteria. The stochastic fisheries model relies on a hockey-stick recruitment function with wide variance, generating occasional extremely large recruitment. In response to stock variability, we examine linear harvest strategies which close the fishery when estimated biomass falls below a stipulated given minimum biomass level (B_{min}), and set catch quotas as a fraction of the surplus of existing biomass above the minimum biomass level ($B_y - B_{min}$). To simulate the variability of results from each strategy we performed 1,000 50-year simulations. The results are summarized as average and variance of annual harvest, biomass and 50-year Net Present Values (NPV) for the fishery. This study concludes that the harvest strategy with low minimum biomass (5% of unfished biomass) and low fraction (0.2) would be desirable for three reasons: (1) maximization of NPV, (2) stochastic dominance and (3) biomass conservation.

Keywords: bioeconomics, stochastic model, fluctuating fish stock, Pacific whiting fishery

INTRODUCTION

All marine fish populations fluctuate in abundance. This leads to unavoidable changes over time in commercial catches. Variability in catch is generally an undesirable characteristic because of two well known economic consequences (e.g., [1]). First, if the market demand is price elastic, this further destabilizes fishing revenues. We don't explore this first aspect. Second, unless capital equipment can be shifted quickly among fisheries at little or no cost, the annual capital expenses rise with increase fluctuations. Hence, the net economic yield (expected net present value) is typically higher with more stable annual harvest levels. This capital cost issue is incorporated in our assessment. Furthermore, from a biological viewpoint, stability in fish abundance is desirable as it reduces the danger of extinction [2].

The fishery for Pacific whiting is the largest fishery, by volume, off the U.S. and Canadian Pacific coasts. The life history and biology of Pacific whiting has been summarized in Helser et al. [3]. Still uncertain, however, are the causes of the extreme variability in recruitment, and the reason that the annual migration pattern varies greatly. Both of these uncertainties have major impacts on the fisheries for Pacific whiting. The most important of these is recruitment variability; recruitment of Pacific whiting can be extremely large and totally independent of the size of the spawning stock. The presence or absence of large year-classes leads to substantial changes over time in abundance, imposes the need for altering annual harvest quotas by significant amounts (e.g., difficulty in setting biological reference points), and influences investment decisions in the whiting fisheries.

The Pacific whiting the stock typically migrates northward from southern California spawning areas to Oregon, Washington, and southern British Columbia each spring, with the more mature fish migrating further north. Because the same stock is harvested by U.S. and Canadian fisheries, a multi-national management agreement is needed. Further, within the U.S. fishery, there are distinct fishing sectors, including at-sea processors (motherships and factory trawlers[a]), a trawl fleet delivering to on-shore processors[b], and a tribal fishery[c]. The Canadian fishery involves on-shore processors and joint ventures with Russia and other Eastern Europe countries. The migratory patterns, multiple fishing sectors, and bi-national management pose interesting challenges for the management system.

The purpose of this paper is twofold. One goal is to describe a stochastic bioeconomic model for the Pacific whiting fishery which captures the occasional extremely large recruitment events and expresses the complex structure of fishing sectors in the Pacific whiting fisheries. A second goal is to explore fishing harvest strategies which reduce the effects of a fluctuating fish stock in the benefit of the Pacific whiting fisheries. A Monte Carlo simulation model is used to capture these features.

Although we have constructed the fishery model to include fishing activities of all sectors in U.S. and Canada, our economic model focuses on the U.S. fleet that delivers to shore-based processors. The aggregated harvesting–processing operations of the other sectors are included in the harvest and whiting stock calculations. This focus was chosen because the harvesting and processing operations of the shore-based sector of U.S. are more transparent. Operators in the U.S. shore-based sector have distinct and separate firms in whiting harvesting and processing. In contrast, the earning of catcher boats in the at-sea (mothership) operations is a share of processors' (i.e., motherships) net revenue rather than the direct earnings from selling their harvest[d]. In the case of factory trawlers, harvest and processing activities are aggregated, and cannot be distinguished as separate economic activities. In both at sea-sectors, therefore, it is difficult to estimate the value of harvesting independently from that of processing. Catcher boats in the shore-based sector, however, earn revenue by direct sales of harvest to processing factories. This allows the calculation of the net value of harvesting under effects of a fluctuating fish stock.

DISCRIPTION OF BIOLOGICAL MODEL

Ishimura et al. [4] developed the stochastic pacific whiting population dynamics model which includes a hockey stick stock recruitment function tailed to generate occasional extremely strong year classes. This study integrated that model into a simple economic model the U.S. shore-based Pacific whiting fishery.

Population dynamics model

The population dynamic model assumes exponential decline model that fishing and natural mortality occur continuously throughout the year. Recruitment is modeled as occurring at age 2 and all fish 15 years and older are pooled into a 15 year plus-group. The model keeps track of the 3+ biomass. The weight of a fish of age is assumed to be time-invariant and equal to the weights-at-age for 2001 (detailed model description is in Ishimura et al. [4] and Ishimura [5]).

Spawning stock biomass and recruitment model

Two extremely large recruitments (the 1982 and 1986 year spawning biomass-classes) make it difficult to identify the underlying nature of the stock-recruitment relationship of Pacific whiting (Fig.1). To incorporate this range of variability we adapted a spawning stock recruitment (SR) model with an additive error term that permits occasional, extremely large recruitments.

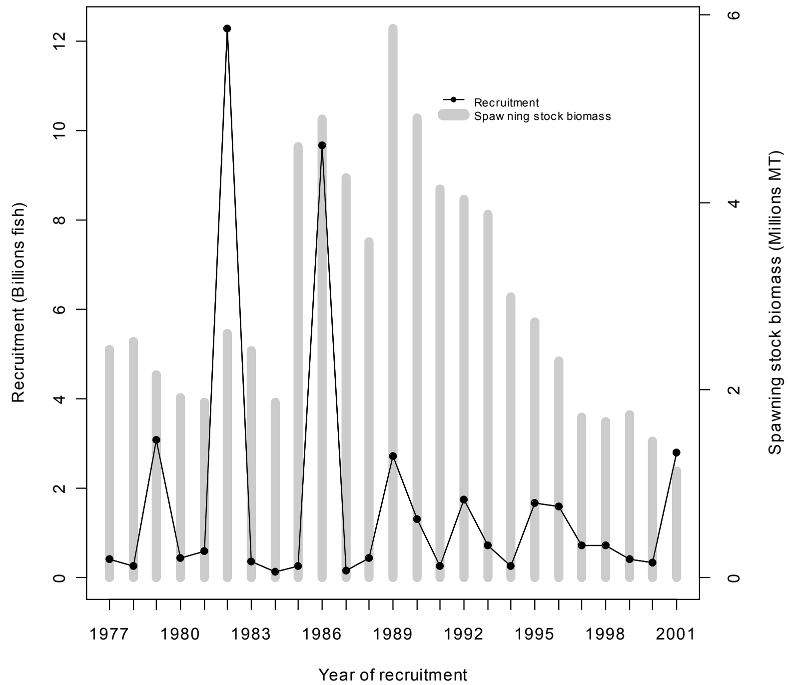

Figure 1. Maximum likelihood estimates of the annual number of 2-year-old Pacific whiting (recruitment) and the corresponding spawning stock biomasses

Ishimura et al. [4] applied a hockey stick SR model which shows a linear increase in recruitment from the origin to a threshold biomass level, S*, after which recruitment is constant at a level of recruitment R^* (Eq.1 and Fig. 2)[e].

$$R_{y+2} = \begin{cases} \alpha S_y = R^* \dfrac{S_y}{S^*} & \text{if } S_y < S^* \\ \alpha S^* = R^* & \text{if } S_y > S^* \end{cases} \qquad \text{(Eq. 1)}$$

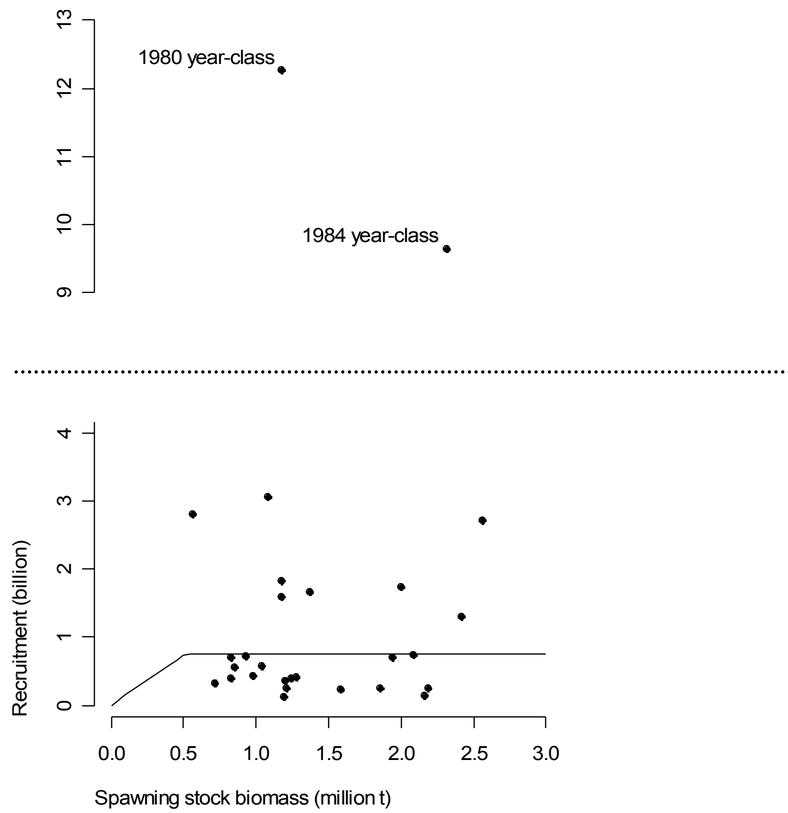

Figure 2. Fit of the hockey stock stock-recruitment relationship (solid line) to the maximum likelihood estimates of spawning stock biomass and recruitment (solid dots)

Current assessment of Pacific whiting is based on a Bayesian approach which involves applying the Markov Chain Monte Carlo (MCMC) algorithm to sample large numbers of parameter vectors from the joint posterior distribution for the parameters [3]. For recruitment, this process involves updating prior distributions for mean recruitment and the annual deviations in recruitment about that mean using data on catch-at-age from the commercial fisheries and survey data. The MCMC algorithm can also be used to generate spawning biomass and recruitment data sets. In order to reflect the variability arising from the Bayesian assessment in terms of the values for the parameters of a hockey stick SR model (parameter uncertainty), this model was fitted to 1,000 stock-recruitment data sets generated from the posterior distribution. As the result, the covariance structure of two parameters, S* and R*, are created. For each simulation of 50 years, a set of parameter is randomly chosen from this covariance structure of S* and R***.**

A key objective of this recruitment model is to capture the impact of occasional extreme recruitments, as well as the impact of "normal" variability in recruitment about the deterministic stock-recruitment model. Therefore, for each year of the projection period, the following procedure is applied to generate annual recruitment (age 2) for year *y*. Two occasional extreme recruitments are observed out of 28 years. Thus, first generate a random variable, Δ, from U[1,28] and compute the recruitment for year y expected from the stock-recruitment relationship. If Δ is 26 or less, the year is a "normal" year (i.e., environmental conditions do not lead to extreme recruitments) and the recruitment for year y is generated based on the error obtained from the residuals about the fit of a hockey stick SR model to the stock and recruitment data (ignoring the residuals for the 1982 and 1986 recruitments). If Δ is 27 or 28, an "extreme recruitment" is assumed to occur and the actual recruitment for year *y* is then generated by adding the largest and second largest residuals about the fit of the stock-recruitment model to the data (detailed of SR analysis of Pacific whiting and modeling procedures in Ishimura [4]).

DISCRIPTION OF ECONOMIC MODEL

The Pacific whiting fishery is a part of the multi-species, U.S.West coast groundfish fishery. Therefore, the fishery economic model accounts for vessel operating cost only during the time spent in the fishery for Pacific whiting. Fishing effort was measured as days fished with a harvest capacity defined in the same units. This day-standardized fishing effort makes explicit the link between a vessel's economic activity and fishing mortality.

Catch Per Trip (fishing effort)

Catch per trip is assumed to remain constant[f] at recent levels, 70 t per trip (the average of 1997-2002), irrespective of the future size of the resource. This catch per trip is combined with operational cost information (see the following section) to calculate the economic returns to the shore-based catcher boat sector.

Ex-vessel price and Vessel operation costs

This study uses the average of the 1997-2000 ex-vessel prices for the U.S. shore-based sector ($ 0.084 / kg) as the ex-vessel price. Table I shows the estimated operational cost for a catcher boat per day fished. Variable costs, which depend on the duration of the operation (i.e. searching / fishing time, the number of trips), include payments to the crew and skipper, fuel and lube, and "other costs" (which include insurance for the crew and skipper). The duration of a fishing operation is standardized to "per day fished". Fixed costs, which are defined by fiscal year, include vessel- and gear-associated payments, insurance for vessel operations, recruitment and employment-associated costs, and "other costs" (which include mooring payments and administrative fees). These fixed costs are also shown as "per day" based[g] in Table I.

Table I: Estimated operational cost of a catcher boat

		Per day
Variable Costs	Payment to the crew and skipper	**$1,250**
	Fuel and lube	**$750**
	Other costs	**$200**
Fixed Costs	Vessel and gear associated payments	**$1,000**
	Insurance associated with vessel operation	**$300**
	Recruitment, travel, benefits and other employee-related costs	**$50**
	Other costs	**$800**
	Total of variable and fixed costs	**$4,350**

Net economic return and loss during "non-fishing" years

Catch per trip and cost per day (operational costs) need to be combined to calculate the net economic returns. In 2002, the average number of days per trip was 1.77 (SD 1.39)[h]. The total operational cost per trip is assumed to be equal to the operational cost per day ($4,350 per trip; Table I). Under the assumption of a 70 t catch per trip, the gross revenue is \$5,880 per trip (\$0.084/kg multiplied by 70 t/trip). Subtracting the operational cost per day from the gross revenue, the net economic return is calculated as \$1,530 per trip.

In the simulations, the entire Pacific whiting fishery is closed if the estimate of the total biomass drops below a "minimum biomass level" which is a part of the fishery management strategy (see next section). Although the variable costs associated with fishing do not occur if the fishery is closed, fixed costs still occur unless the catcher boats have alternative harvest opportunities. For the purposes of this study, fixed costs are assumed to occur in any "non-fishing" years without alternate fishing revenue. An annual average of accumulated 1,100 trips by the shore-based fishery took place during 1997-2002. Given the fixed cost per day (\$2,150/day), this implies a fleetwide fixed cost of \$2,365,000/year that occurs even when the fishery is closed. In the simulations, we assume that the fleet has no good alternative uses during the occasional fishery closure, and we charge the full \$2,365,000/year fixed cost regardless of whether fishing is permitted[i].

DISCRIPTION OF MANAGEMENT MODEL

Stock assessment

The Total Allowable Catch (TAC) for Pacific whiting is calculated using the biomass of fish aged 3 and older (the 3+ biomass) as a proxy, unless specified otherwise. Estimated biomass in the stock assessment is determined by adding the temporally auto-correlated normally-distributed observation error with coefficient of variation, CV of 0.15[j] to the actual 3+ biomass, i.e.,:

$$\begin{cases} \hat{B}_y = B_y(1+\eta_y) & \text{if } \eta_y < 1 \\ \hat{B}_y = 0 & \text{if } \eta_y \geq 1 \end{cases} \qquad \eta_y = \rho\eta_{y-1} + \sqrt{1-\rho^2}\,\xi_y \qquad \xi_y \sim N(0;\sigma_\theta^2) \qquad \text{(Eq. 2)}$$

where ρ is the extent of temporal auto-correlation in the observation errors and
σ_θ is the standard deviation of the observation errors (taken to be 0.15)[k].

Temporally auto-correlated observation error is considered because observation errors are not independent; over-estimation of biomass in one year will usually imply over-estimation of biomass in the following year. The extent of temporal auto-correlation (ρ) in observation error is assumed to be 0.5.

Total Allowable Catch

The "Fraction/Minimum biomass" strategy includes the biological reference point (B_{min}, minimum biomass) that depends on B_0, the unfished 3+ biomass which is calculated by the average recruitment in the absence of fishing mortality[l]. The "Fraction/Minimum biomass" harvest strategy defines the TAC as:

$$TAC_y = \max\left[0, \left(\hat{B}_y - B_{min}\right)\cdot\Omega\right] \qquad \text{(Eq. 3)}$$

where B_{min} is a minimum biomass for fisheries and
Ω is a given harvest fraction.

Minimum biomass is assigned as

$$B_{\min} = \Psi \cdot B_0 \quad \text{(Eq. 4)}$$

where Ψ is a given minimum biomass fraction relative to the unfished biomass.

This implies that the fishery will be closed if the biomass is estimated to be less than the minimum biomass and that the catch limit will increase linearly with biomass increased if the biomass is estimated to be larger than the minimum biomass. This harvest strategy is appropriate for examining the direct consequences on catch of fluctuations in biomass.

The combination of a higher minimum biomass and a lower harvest fraction places greater emphasis on stock conservation. In other words, if the management objective is stock conservation, the manager should choose a high minimum biomass and low harvest fraction. On the other hand, a management strategy more focused on maximizing annual average catch would select a somewhat lower minimum biomass and higher harvest fraction. A total of 110 combinations of 11 fractions {Ω=0.05 and from 0.1 to1.0 by 0.1} and 10 minimum biomasses {Ψ =0.05 ($0.05B_0$) and from 0.1 ($0.1B_0$) to 0.9 ($0.9B_0$) by 0.1} are considered in this study.

Allocation and utilization of quota

Allocation of Pacific whiting quota (TAC) consists of two steps: (a) the international allocation between the U.S. and Canada (76:24), and (b) the allocation of the U.S/Canada quota among domestic sectors.

The allocation of the U.S. domestic quota among sectors is assumed to be the same as of 2002: at-sea (motherships) 14%, at-sea (factory trawlers) 29%, shore-based 36%, and Tribal 14%. The bioeconomic model calculates the economic return for the 36% quota share taken by the U.S. shore-based sector. Furthermore, we assume full utilization of quota for each year up to assigned annual fishing capacities of each sector[m].

SIMULATION RESULT

With the integration model of the biological, economics and management models, 1000 simulations of a 50-year projection period are conducted for each harvest strategy, then the average net present value (NPV) for 50 years and average biomass were calculated.

Figure 3 shows selected the average NPV for the U.S. shore-based fishery versus the standard deviation of the annual average catch for 110 variants of "Fraction/Minimum biomass" harvest strategy. Each line in Figures 3 represents a specific choice for the fraction of the unfished biomass (Ψ) when applying the "Fraction/Minimum biomass" harvest strategy and a range for the fraction (Ω) removed given that the 3+ biomass exceeds the minimum biomass. Considering a single line, the value of Ω increases from the lowest value considered (Ω=0.05) corresponding to a point close to the x-axis to the largest fraction consisted (Ω=1).

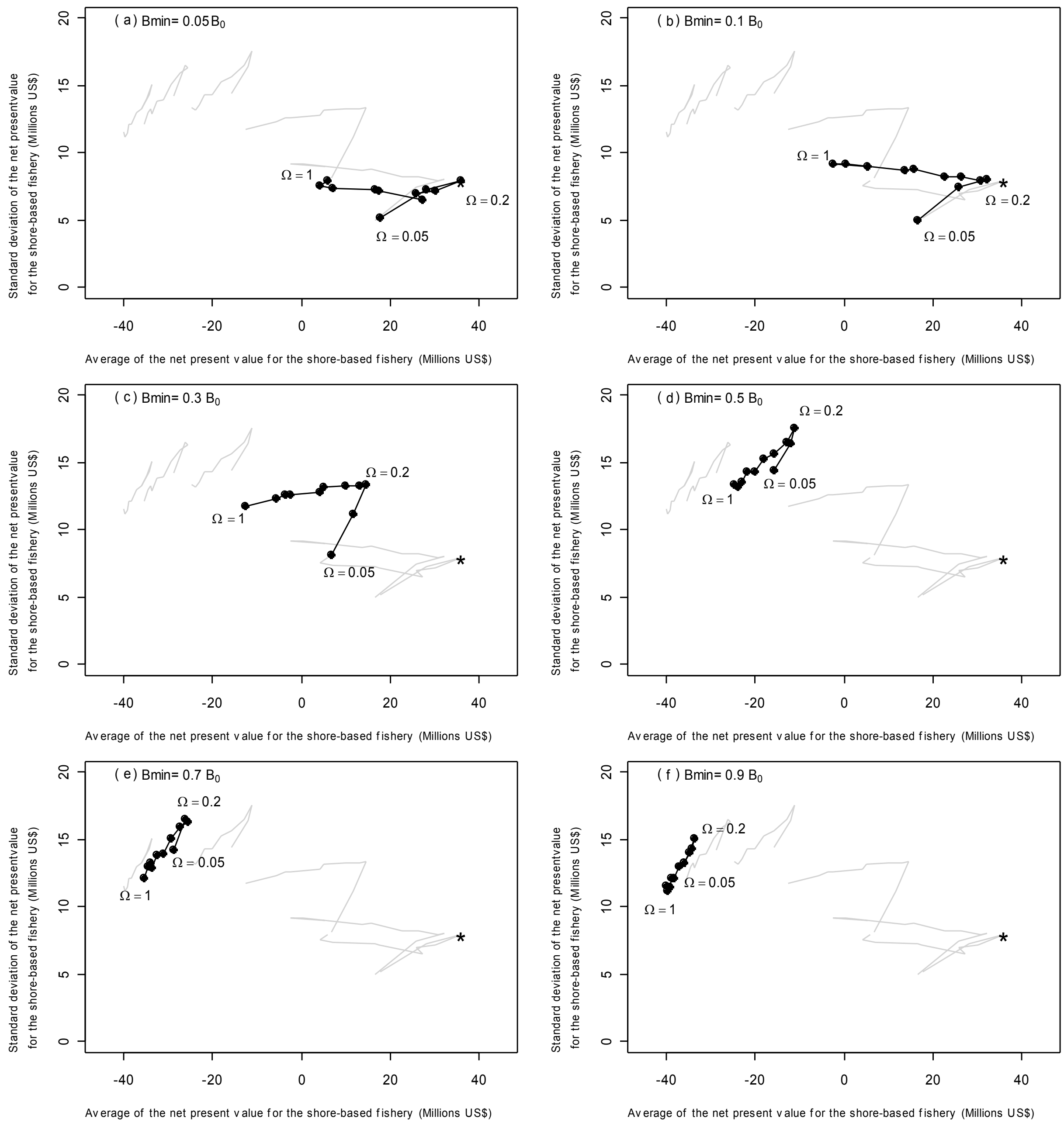

Figure 3. Average and standard deviation of the net present value for shore-based fishery (units are millions of US$) for 110 "Fraction/Minimum biomass" harvest strategies. Each box highlighted selected minimum biomass strategies. "*" indicates the performance of maximum average annual total catch (Ω=0.2, B_{min}=0.05B_0)

NPV for the U.S. shore-based fishery "bend backwards" (i.e., mean economic yield rises with increasing Ω and then begins falling) for all choices for the minimum biomass. The "backwards bending" occurs because of the negative economic returns occurring during fishery closures. Several of the harvest strategies lead to negative net present value on average. The net present value of the shore-based fishery is maximized ($35,955,316) using the same strategy that maximized average annual catch (minimum biomass = 0.05B_0; Ω=0.2).

Table II shows the simulated average biomass expressed as a percentage of the unfished biomass, B_0. For a given minimum biomass, this ratio decreases as Ω is increased due to the impact of higher fishing mortality rates. Average U.S. shore-based NPV is maximized when this ratio is about 40% of the unfished level, (i.e., 0.4 B_0 at minimum biomass = $0.05B_0$; Ω =0.2). The average biomass drops markedly between Ω =0.2 to 0.3 for minimum biomass = $0.05B_0$ (42% to 24%). This drop reflects to more frequent fishery closures.

Table II: Average biomass expressed as a percentage of the unfished biomass (B_0) for the 110 "Fraction/Minimum biomass" harvest strategies (standard deviations are in parentheses)

Fraction(Ω)	***0.05***	***0.1***	***0.2***	***0.3***	***0.4***	***0.5***	***0.6***	***0.7***	***0.8***	***0.9***	***1***
$0.9B_0$	84 (44)	81 (41)	76 (37)	72 (35)	70 (33)	69 (33)	68 (32)	67 (31)	67 (31)	67 (31)	66 (31)
$0.8\ B_0$	83 (43)	78 (39)	74 (36)	70 (34)	68 (32)	67 (31)	65 (30)	65 (30)	63 (29)	63 (29)	63 (29)
$0.7B_0$	81 (42)	77 (39)	70 (35)	67 (32)	65 (30)	63 (30)	62 (29)	61 (29)	61 (29)	60 (29)	59 (28)
$0.6B_0$	81 (48)	74 (38)	69 (34)	64 (31)	61 (29)	60 (29)	58 (28)	58 (28)	57 (27)	56 (27)	56 (28)
$0.5B_0$	79 (41)	73 (38)	65 (33)	60 (30)	58 (29)	56 (28)	55 (28)	54 (27)	53 (27)	52 (27)	52 (27)
$0.4B_0$	77 (40)	71 (37)	61 (32)	56 (30)	53 (28)	51 (26)	50 (27)	48 (26)	48 (26)	47 (26)	46 (26)
$0.3B_0$	77 (43)	67 (37)	56 (32)	51 (29)	47 (28)	44 (26)	44 (27)	40 (24)	40 (25)	40 (25)	36 (23)
$0.2B_0$	75 (41)	63 (35)	51 (31)	44 (28)	39 (26)	34 (22)	34 (24)	30 (20)	29 (20)	28 (19)	27 (18)
$0.1B_0$	71 (41)	59 (36)	43 (29)	32 (23)	26 (20)	23 (19)	20 (16)	19 (16)	15 (11)	15 (11)	17 (15)
$0.05B_0$	70 (41)	57 (36)	**42** (30)	**24** (21)	18 (17)	17 (17)	13 (13)	12 (13)	10 (10)	10 (10)	10 (10)

CONCLUSION

The primary objective of this study was to assess fishing harvest strategies for both mean and variance of economic returns with a fluctuating stock of the Pacific whiting. General trends in the relationship between the average NPV of U.S. shore-based Pacific whiting fishery and variance in NPV were examined. The relationship between NPV and its variance is non-linear because of the impact of resource depletion and due to the fixed costs fishing when the fishery is closed. A harvest strategy is said to be "stochastically dominated" by another harvest strategy if the two strategies yield have the same NPV but the second has a lower variance of NPV. The selection of a "best" harvest strategy from those considered in this paper should therefore be restricted to those harvest strategies that are stochastically dominated (assuming that all perform adequately in terms of resource conservation).

At noted above, harvest strategies with B_{min}=$0.05B_{0,}$ Ω=0.05 and those with and Ω=0.1 and Ω=0.2 stochastically dominate the remaining harvest strategies. Of these harvest strategies, the last (Ω=0.2) is perhaps most desirable because it maximizes the average NPV but is much less variable than many of the other harvest strategies. A particularly desirable feature of this harvest strategy is that it almost never leads to closure of the fishery [4].

The results described in this paper imply that a harvest strategy with a relatively low minimum biomass combined with a relative low harvest fraction is more desirable than a harvest strategy that is conservative (high minimum biomass) but set high catches if the biomass is above this minimum biomass. Reasons for this include:

1) Setting harvest as a low fraction of ($B_y - B_{min}$) reduces the effect of stock fluctuations variance in economic yield. In other words, using a low fraction reduces uncertainty of net present value.

2) Using a low fraction maintains a higher biomass level (i.e., biomass conservation).

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REFERENCES

[1] Hannesson, R. 1993, Bioeconomic analysis of fisheries. Fishing-News-Books ,Oxford-UK.

[2] Steinshamn, Stein I. 1998, Implications of Harvesting Strategies on Population and Profitability in Fisheries. *Marine Resource Economics*, 13(1), pp 23-36.

[3] Helser, E.T., Dorn, M.W., Saunders, M.W., Wilson, C.D., Guttormsen, M.A., Cooke, K., and Wilkins, M.E. 2002, Stock assessment of Pacific whiting in U.S. and Canadian Waters in2001. Pacific Fishery Management Council, Portland, OR.

[4] Ishimura, G., Punt, André E. and Huppert, Daniel D. 2004. The management of fluctuating fish stock- the case of Pacific whiting. Submitted to *Fisheries Research*

[5] Ishimura, G, 2003, Bioeconomic model approach for a fluctuating fish stock: bioeconomic assessment of harvest strategies for the Pacific whiting fishery, Master Thesis of the University of Washington. University of Washington, Seattle.

Endnote

[a] A mothership engages 3-10 catcher boats in harvesting operations and just process harvest from catcher boats. In contrast, factory trawlers catch and process independently and usually do not have associated catcher boats.
[b] On-shore processors process harvest from catcher boats.
[c] Tribal fisheries operate as the same as mothership operation.
[d] The recent trend is based on a risk-sharing business strategy in the market.
[e] This presentation is predicated on a given selection of the set for R* and S*in the Maximum Likelihood Estimation in the stock assessment. .
[f] This implies the catch per trip is independent of the abundance of the fish population.
[g] This is equal to Fixed cost divided by days in a fiscal year.
[h] Personal communication from Dr. Steve Parker Oregon Department Fish and Wildlife (2002).

[i] When fishing is permitted, this fixed cost is calculated into the net economic return as per day and vessel (see Table. I).
[j] This is the CV for the biomass estimates based on the Bayesian assessment of Pacific whiting.
[k] The value η_y for y=1 is generated from N(0; σ_θ)
[l] See Ishimura [4] for calculation details.
[m] See Ishimura [4] for detailed capacity estimation.