The Development of a Bioeconomic Model for the Oregon Ocean Shrimp Fishery

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Selecting 'optimal' strategies to manage Oregon ocean shrimp is challenged by uncertain and variable natural mortality, recruitment, and growth. Fishery management is focused on measures to prevent long-term biological damage to the stock, to protect age-1 shrimp from overharvest and to sustain long term fishery benefits. Developing harvest strategies such as mesh size and season dates are complicated by economic factors including differences in output prices as a function of shrimp size. To address these questions economic information was integrated with biological data to develop static and dynamic bioeconomic models. Equilibrium biological yield per recruit and revenue per recruit models indicate that a delay in the season opening of this fishery would generate increased revenue as a result of shrimp growth and size-based price differentials. Results using a dynamic non-linear programming model indicate targeting fishing intensity later in the season can generate better yield and revenue. Sensitivity analysis indicates that higher rates of natural mortality will decrease the benefits of delaying the season opening. Future research will build on this analysis by including selectivity at length, variable recruitment, harvester and processor costs, and product quality.

Keywords: Bioeconomic modelling, yield per recruit, fishery management, seafood markets

1.0 INTRODUCTION/PURPOSE

The Pacific Ocean shrimp fishery, *Pandalus jordani*, has been under tri-state management since 1950's. A Pacific Fishery Management Plan for shrimp was developed in 1980 (PFMC, 1981). Plan objectives preventing biological growth and recruitment overfishing and promoting the economic value of the shrimp resource. Historical management of the fishery has included policy measures to allow age 1 shrimp to escape the catch and to allow berried females to release juvenile shrimp. Presently, the trawl fishery manages the fishery using: (1) a minimum mesh size restriction of 39mm in the trawl nets; (2) a minimum count per pound (CPP) restriction of 160 shrimp per pound on landed catch; and (3) a closed season from November-March. However, the recent dependence of the fishery on age-1 shrimp indicates this may be a highly recruit-dependent fishery, making it susceptible to over-exploitation (Jones and Hannah, 1995).

Recruitment of ocean shrimp is believed to dictate how well the fishery will perform in the following season. Recruitment is negatively correlated with the April sea level height which provides a proxy for the timing and strength of the spring transition (Hannah, 1997). Recent research has provided evidence that the late release larvae have a better chance for survival in poor recruitment (weak Spring Transition) conditions. Managers are now considering a delay in the season opening to allow egg bearing females an increased chance to avoid capture and successfully release larvae.

A comprehensive study was designed to investigate biological, economic, and management issues important to this fishery. Industry surveys collected biological, market and shrimp quality information and were incorporated into static and dynamic optimization models to compare the results of biological and economically based management policies.

This paper specifically addresses the potential gains in yield and revenue from a potential management decision to delay the season opening. This management is designed to ensure increased growth of age 1 shrimp and allow late bearing females to release larvae prior to capture to improve recruitment This paper develops yield per recruit (YPR) and revenue per recruit (RPR) models for the Pacific Ocean shrimp, *Pandalus jordani*, fishery.

2.0 CONCEPTUAL MODEL DEVELOPMENT

Maximizing harvest or surplus production may not maximize revenue or other management objectives. This is particularly true if market output price depends on the size of harvested product. For rapidly growing stocks or stocks whose condition may vary seasonally, the timing of harvest may be an important decision variable. When dynamics are introduced, the choice to the fishery manager is both timing and intensity of harvest to maximize biomass yield or revenue or some other economic objective such as jobs or rents. In this case the rate of fishing mortality is a function of time and could vary throughout the season.

2.1 Classic Equilibrium Yield Per Recruit

The initial generation of a single cohort yield per recruit analysis for Pink Shrimp, *Pandalus jordani,* incorporates equations to track the population across seasons and over a four year time period. The objective for the fishery manager is to determine the optimum combination of age at entry and fishing mortality rate that will produce the greatest biomass yield to the fishery.

The analysis incorporates equilibrium conditions using constant (knife-edge) recruitment, constant natural and fishing mortality, and a constant age at entry for all shrimp cohorts. The model is based on the static Beverton and Holt (1959) model with a dynamic pool assumption allowing a unit stock to be treated as a perfectly mixed age group with homogenous distribution and equal probability of capture. Therefore, the total biomass yield obtained from a single cohort of shrimp over four years is identical to the annual biomass yield (at equilibrium) to be obtained from a shrimp population that consists of all four cohorts (age 0 age 1 age2 and age3 shrimp). In equilibrium, summing over age classes, the total annual yield from all cohorts equals the total lifetime yield from a single cohort (Clark, 1990).

In this model, the shrimp are released at time, t_0 , which is March1of year 0. They experience a 2-3 month pelagic larval stage, then settle on the shrimp grounds at about 3 months. The age of recruitment, t_r=12 months corresponds to March 1 of year1. The age of entry, t_e, is referenced as t_e = month 13 which is April 1 of year 1.This model uses a knife edge selectivity assumption equal to month 12. This means that at age t_r all age 1 shrimp are vulnerable to the gear. Therefore,

$$N(t_r) = R \qquad (1)$$

where R is the number of recruits to the fishery. However, the age of entry to the fishery, t_e, is the chosen date to open the fishery. The age of entry is a result of both season opening and mesh size.

$$N(t_e) = N(t_r)*\exp(-Z*t). \qquad (2)$$

where t =1 month and t_e-t_r=1 month. Therefore,

$$N(t) = N(t_e)* \exp(-Z(t-t_e)) \qquad (3)$$

$$N(t) = N(0)*\exp(-Z*t) \qquad (4)$$

in discrete terms this is identical to:

$$N(t+1) = N(t)*\exp(-Z*1) \qquad (5)$$

The discrete form of the catch equation was used to include the average catch over a month period between the abundance from the month of catch and the prior month (time averaged abundance).

$$C(t) = [N(t) + N(t-1)/2]*(F/Z)*[1-\exp(-Z*t)] \qquad (6)$$

To determine time averaged biomass, the average weight between the months of capture is included.

$$B(t) = \{1/2[N(t)+N(t-1)]*1/2[w(t)+w(t-1)]\} \qquad (7)$$

In equation (7) B (t) represents the average biomass over a month. Oregon Department of Fisheries and Wildlife (ODFW) samples the shrimp catch from the 10th to the 20th of each month to obtain the average weight of shrimp each month. Therefore, the equation (1/2(w(t)+w(t-1)) has been removed and the equation becomes:

$$B(t) =1/2[N(t)+N(t-1)]*w(t) \qquad (8)$$

To determine catch in yield, Y(t), the catch in numbers is multiplied by the average weight of the shrimp at age.

$$Y(t)=\sum[C(t)*w(t)] \qquad (9)$$

The number of recruits is then divided into the yield:

$$YPR = Y(t) / R \qquad (10)$$

Individual growth in this fishery is based on the length at age from commercial fishery sampling data from ODFW for the Stock Unit identified as the region adjacent to Oregon from 1981-1998. A linear regression estimate of the length weight relationship from Zirges et. Al (1982) and Hannah and Jones (1991) provides an allometric equation for the growth of ocean shrimp.

$$W(t) = .0003441 *L(t)^{3.20973} \qquad (11)$$

Monthly natural mortality M, and fishing mortality F, rates are components of the total instantaneous monthly mortality rate Z, where

$$Z = M + F \qquad (12)$$

when F = qf the equation becomes:

$$Z = M + qf \qquad (13)$$

Where f is nominal fishing effort per month and q is the catchability coefficient The catchability coefficient is estimated from catch per unit effort data using Baranov's catch equation (Hannah, 1993).

Values for monthly fishing mortality are taken from the PFMC, 1981 Shrimp Management Plan Table A6-3. The range of fishing mortality values from 1972-1975 for CA, OR and WA are from .0013/mo to .3201/mo. A range from .001 per month to .27 per month is used in this simulation. The range of fishing mortality rates used in the generation allows a complete view of the effects of high harvest rates on shrimp populations.

Natural mortality rates are obtained from previously published estimated rates of commercial fishery catch and effort data as well as biological samples from the commercial catch (Zirges 1982, Hannah 1995). Assuming a constant stock area, the catchability coefficient should also be constant at fishing catchability efficiencies (q) of 25, 50 and 75 percent. Back calculations to estimate reasonable values for monthly natural mortality for age 2 ocean shrimp are provided in Hannah 1995 using the catch curve methods.

For the models presented, natural mortality is divided into winter and summer natural mortality rates as a result of increased predatory pressure from the age 2-7 hake migrating population in the Summer season (Hannah, 1995). Winter natural mortality rates, Mw, are found to occur from November to March. Summer natural mortality, Ms, occurs from April-October.

To address a possible fishery management decision to delay the season opening, a single season multiple cohort model was designed as a modification of the classical yield per recruit model to determine the effects of a delay on all three exploitable age classes of shrimp in the fishery. This is accomplished by summing the catch in yield across cohorts by month in the harvest season. Three age classes were combined in the determination of the biomass at time t within the regular season for shrimp, 1 April- 31 October. The affect of a delay on the season opening will allow additional time for growth and natural, mortality from the three exploitable age classes of shrimp.

2.2 Static Revenue Per Recruit

Shrimp market information was collected from personal interviews of 21 harvesters, 12 processors and 10 brokers. A time series of ex-vessel prices of shrimp were collected from Pacific States Marine Fisheries Commission who collect landings data from Oregon, California and Washington. The shrimp industry is not vertically integrated, therefore only the ex-vessel price is incorporated into the present model. An ex-vessel price-size relationship was estimated using sample data from ODFW, PSMFC, and DFO-Canada from 1988-1998. A price equation similar to a hedonic model was used to identify count per pound, the key quality factor in the determination of ex-vessel price (Larkin and Sylvia, 1999). Dummy variables for yearly differences in ex-vessel price were used in the estimation since price negotiations between harvesters and processors determine annual shrimp prices. A hedonic model can pull out the year effects, since no single year can capture the effects.

The estimated equation suggests a 100 count shrimp change (decrease) will result in processors paying from $.16 more per pound in the nominal price of shrimp. This result is consistent with the survey data. However, in some years a price differential occurs splitting the ex-vessel price into size categories. The ex-vessel price of shrimp is determined from the count per pound mixture landed. This price differential is present in the year 2000 fishery and is incorporated into the revenue per recruit analysis. Table 1 provides the estimated real ex-vessel price equation and price differentials as a function of shrimp size (CPP) in a season.

Estimated Real Ex-vessel Price (base 1989)

EVP =.5922-.0016(CPP)+ d1998*.1383

adj-R^2=.81 CPP p value 0.0001

Present Ex-vessel Price Differentials

EVP=.46 when CPP (0-105), EVP= .41 when CPP (106-147), EVP=.30 when CPP (147-160), and EVP =0 when CPP (160+)

TABLE 1. Estimated Real Ex-Vessel Price Equations and Present Ex-Vessel Price Differential s

The static revenue per recruit model is a modification of the multiple cohort seasonal yield per recruit model. The biomass estimates and catch composition calculations are calculated in terms of weighted average count per pound. The revenue functions use the CPP with the count per pound determinations to obtain revenue per recruit in this model. This revenue equation requires two additional steps: 1) the determination of weighted CPP by month, and 2) The incorporation of CPP by month into the revenue equations to get revenue by month in the fishery. The weighted average count per pound is determined by estimating the biomass of shrimp at age. The catch composition for that interval is multiplied by the CPP for each age class and summed (over all age classes) and divided by the sum of the total catch.

$$CPP(t) = \Sigma C(t)*CPP_i(t)/ \Sigma C_i(t) \qquad (14)$$

The ex-vessel price equation relies on the average weighted CPP estimate to determine the ex vessel price. The revenue is the sum of the ex-vessel price ($/lb.)

multiplied by the monthly sum of yield in pounds over the season.

2.3 Dynamic Optimization Model

Nonlinear mathematical programming is used to model the dynamics for the Oregon Ocean Shrimp Fishery. The model is equivalent to a discrete time optimal control problem (Clark,1990). The model consists of biological and economic mathematical equations to represent each component of the shrimp fishery Equations are solved simultaneously using the nonlinear solver in the General Algebraic Modeling System (Jefferson and Boisvert, 1989).

The dynamic model identifies: (1) the succession of time in years, and (2) the age class of shrimp in years. Months are identified to track season length and recruitment to the fishery. The biological component is based on the age-structured population dynamics previously outlined. The economic component incorporates the biological information with revenue obtained from the ex-vessel price to reveal the revenue gained as a result of a management decision to prevent growth and recruitment overfishing. The time path of harvest is chosen to maximize revenue subject to biological dynamics, economic conditions and shrimp regulations. The time path is determined by allocating effort across months within a season.

The objective of the dynamic model is to maximize yield in the fishery subject to the biological, and fishery management constraints of Pacific Ocean Shrimp. The model can select the level of fishing mortality as well as the months within the legal season to concentrate effort in the fishery. Of particular interest is the potential gain as a result of a delay in the season opening. This model attains equilibrium within 4 years and provides long term information related to the timing and level of harvest as a result of a management decision. In addition, the foregone yield to the fishery can be determined using dynamic analysis.

3.0 EMPIRICAL RESEARCH

4.0 Classic Yield Per Recruit

Figure 1 provides the seasonal multi-cohort isopleth contours for the equilibrium yield per recruit analysis. The three exploitable age classes of shrimp are combined to reveal the effect of a delay of the season opening under equilibrium conditions. The contours provide the combinations of season opening and fishing mortality rates on the yield of shrimp. The 'eumetric curve' in this figure reveals the combinations of F and season opening that maximize YPR for a fixed value of F. If the fishery is presently fishing at a rate of .12 /mo., there is no benefit to delay fishing because the shrimp biomass is declining due to natural mortality. However, if the fishing rate is .24/mo. then a delay of 2-4 weeks would drive the fishery toward the eumetric line and provide an expected increase in yield per recruit from 1.85-1.9 and increase of .05grams per recruit. This value is multiplied by the number of recruits and yields an additional 41,620 lbs to the fishery from increased biomass as a result of the delay in fishing.

3.2 Revenue Per Recruit

The time series estimated ex-vessel price equation is used in the development of the revenue per recruit isopleths in Figure 2. The values provided in the figure are in $US multiplied by 1000 for ease of reference. The estimated equation is provided in real terms based on 1988 dollars and prices are decreased to 1988. The nominal equivalent for the count per pound value in the year 2000 is $US .21 for a 100 count change (decrease). The nominal equivalent is consistent with the year 2000 fishery market information and reflects the importance of size in the determination of ex-vessel price.

Interpretation of the revenue per recruit analysis suggests that at low fishing mortality (F=.12), there is an advantage to delay the season opening to the third week in April. A delay may provide an additional U.S.$.05/per recruit (x1000). The increase to the fishery is then $18,878 in ex-vessel revenue. If fishing mortality is as high as F=.24 the contours suggest opening the season in mid-June to increase the RPR an additional $US .35 (x1000). The increase can provide an additional $132,151 to the fishery. The revenue increase is a result of shrimp growth and a higher value for larger shrimp.

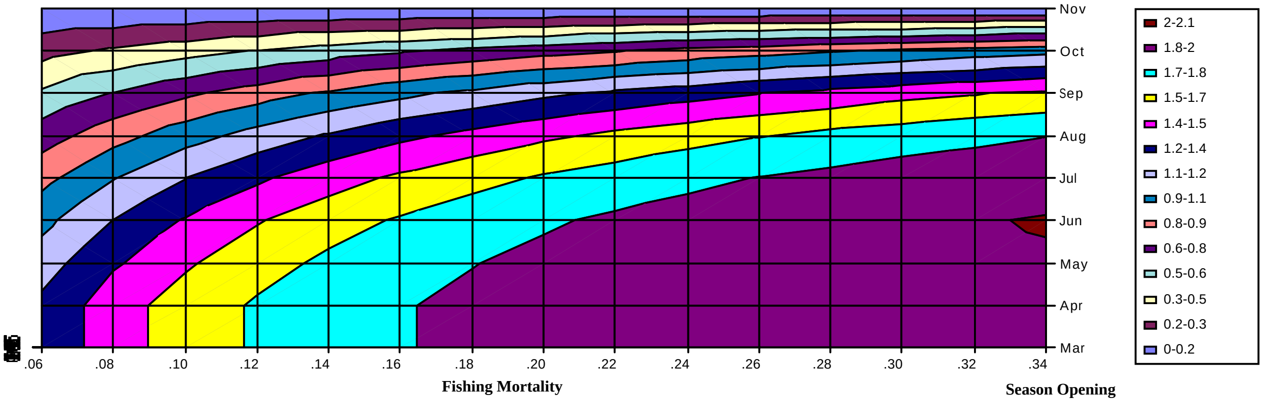


Figure 1. Seasonal multi-cohort yield per recruit isopleths for Pandalus jordani. Summer and winter monthly natural mortality rates are .09 and .06 respectively. Contours are provided in grams per recruit.

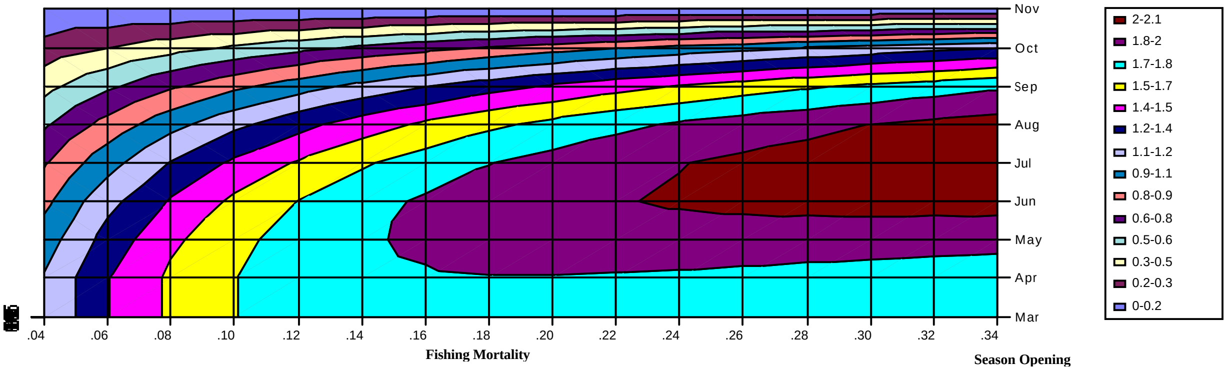


Figure 2. Seasonal revenue per recruit isopleths for *Pandalus jordani*. Summer and winter natural mortality are.09 and .06 respectively. Values are in $US x 1000 per recruit.

3.3 Dynamic Optimization of Yield and Revenue

Results from the Dynamic model are provided in Table 2. The time path of harvest to achieve maximum yield in the fishery reaches equilibrium within 4 years. The data presented are monthly rates of fishing mortality for the season and the monthly count per pound composition as an indicator of shrimp growth.

The dynamic model requires establishing an upper limit to the fishing mortality rate. The upper limit was set at 0.3/mo. to simulate the constraints on the fishery to avoid instantaneous catch. The results indicate that once optimum conditions are met it is optimal to fish at that rate. Note that for a natural mortality rate similar to the YPR and RPR models, a delay of the season opening is beneficial to both yield and revenue.

	DYNAMIC MAXIMIZATION OF YIELD						
Month	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**
CPP	**182**	**165**	**151**	**139**	**128**	**119**	**111**
F(t)	**0**	**0**	**0.3**	**0.3**	**0.3**	**0.1**	**0**
	DYNAMIC MAXIMIZATION OF REVENUE						
Month	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**
CPP	**182**	**165**	**151**	**139**	**128**	**119**	**111**
F(t)	**0**	**0**	**0**	**0.1**	**0.3**	**0.3**	**0.3**

Table 2. Results of dynamic optimization of yield and revenue for *Pandalus jordani*. Count per pound and fishing mortality rates are provided as indicators of harvest timing and intensity.

The Yield model suggests delaying fishing until June in order to maximize yield to the fishery. At this point the model suggests fishing at the maximum rate.

The time series estimated ex-vessel price equation was used for the revenue model. The maximization of revenue suggests a gradual entry to the fishing season and a season opening date in July. The revenue model appears to take advantage of the increasing prices over the season as well as the increasing size of shrimp.

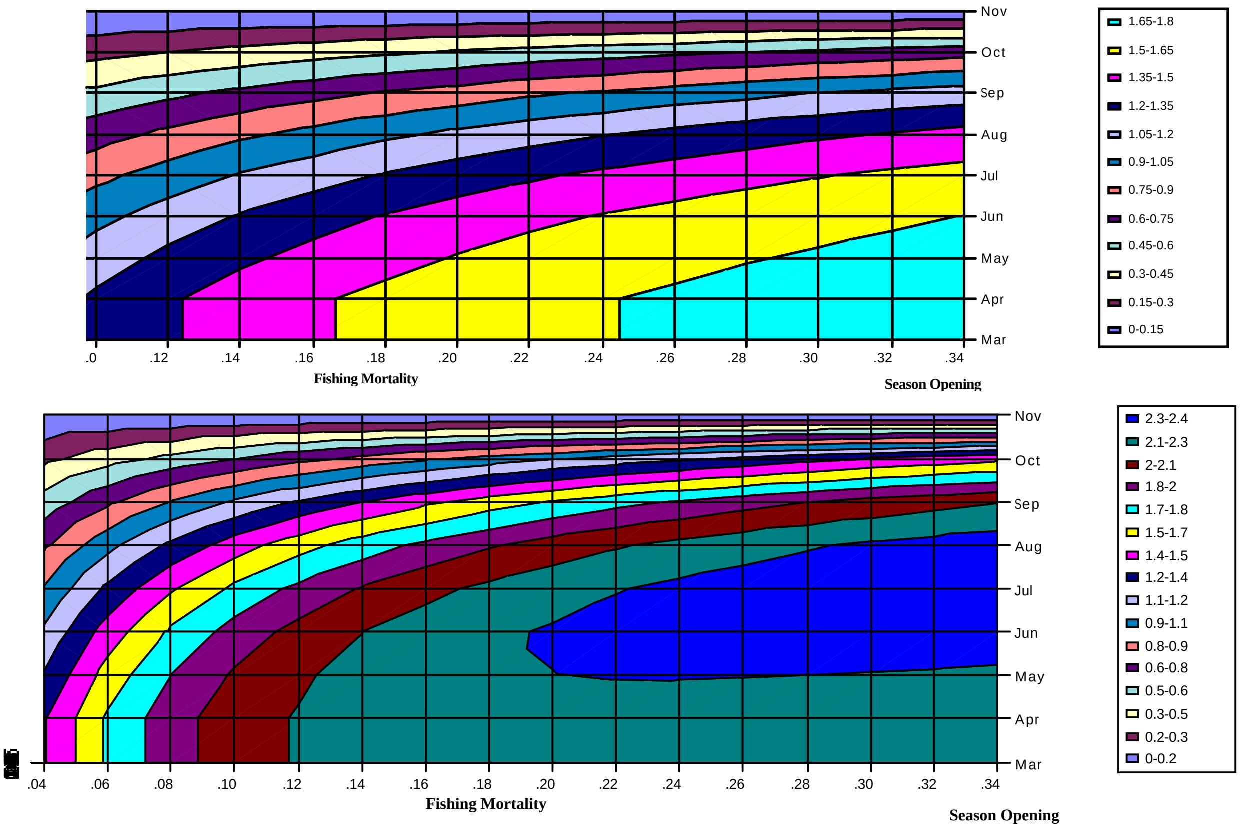
4.0 SENSITIVITY ANALYSIS

Uncertainty about the parameters driving the equations in the model should warrant caution in interpretation of the model results. Natural mortality rates in this fishery have been estimated as early as 1972. However, recent natural mortality rates have been determined from commercial catch per unit (CPUE) data (Hannah, 1993).

Figures 3 and 4 present YPR isopleths that use higher and lower natural mortality rates, respectively. As natural mortality increases, the benefit to delay the season opening decreases. When natural mortality is lower, the YPR value increases and there is greater advantage to delay the season opening.

Sensitivity about the natural mortality rate shows a similar but reduced effect on the revenue equation. As natural mortality increases, there are less revenue benefits as a result of delaying the season opening. A decreased natural mortality will increase fishery value.

Ex-vessel prices are also uncertain. In reality, the CPP available each month of the harvest season will be sensitive to the selectivity of the age 1 shrimp in the catch. The models presented used knife edge selectivity indicating that the driving force behind the biomass is growth and mortality of the shrimp alone. Selectivity



Figures 3 and 4. Seasonal multi-cohort yield per recruit isopleths for *Pandalus jordani* generated from monthly natural mortality rates of .12 summer and .10 winter.(top), .06 summer and .04 winter (bottom).

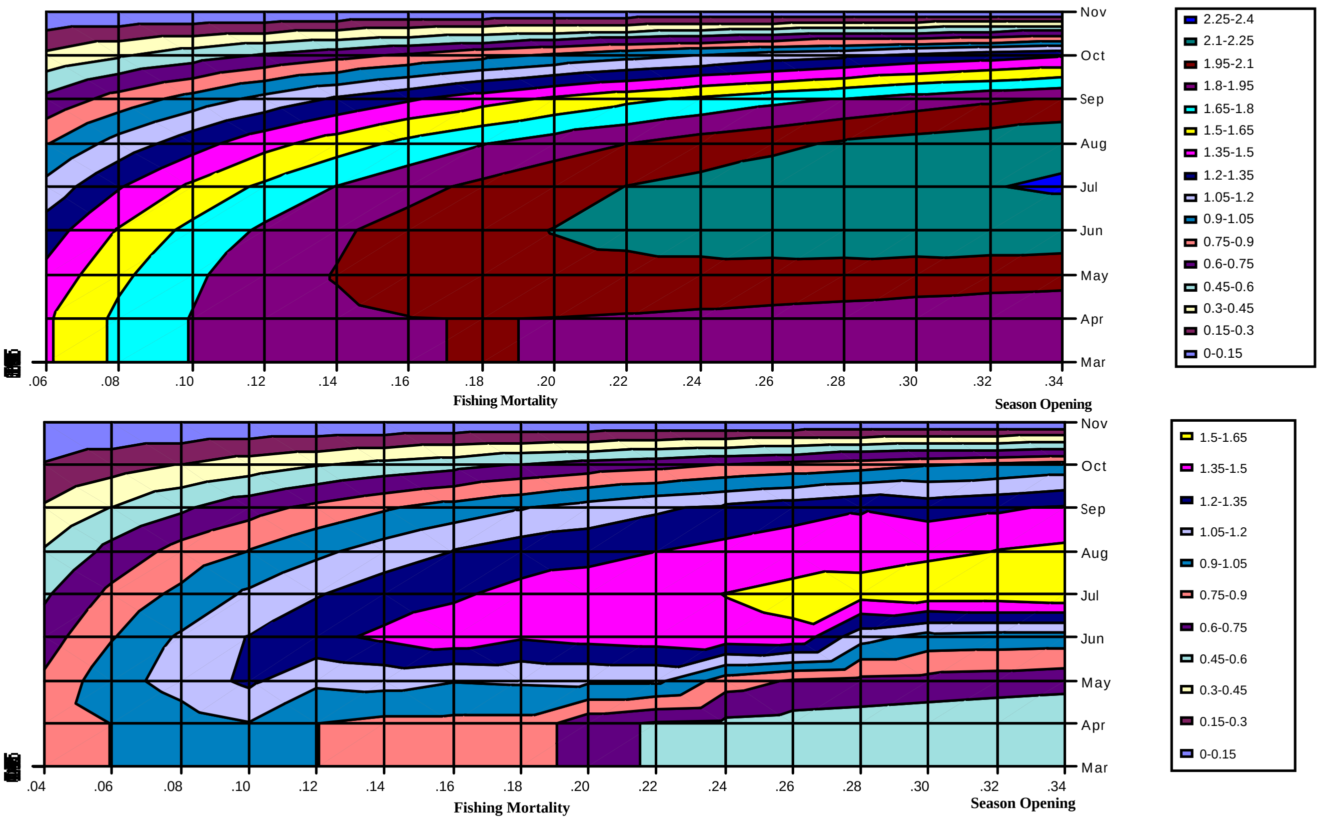
coefficients on the fishing mortality rate can provide a CPP mixture that mimics that observed in the fishery.

Figure 5 presents a steeper and possibly more realistic representation of prices over the season. The ex-vessel price equation is taken from 1994 data as a representative year and better represents the present fishery. The estimated equation is EVP = .83 -.0020 (CPP) adj R^2=.78 p value=.01. There is an increased value in a delay of the season opening over a greater range of fishing mortality rates. Specifically, at fishing mortality rates of .12/mo. the .15 increase in revenue per recruit as a result of a delay to mid-June will generate $56,636 to the fishery. If the fishing mortality rate is as high as .24 the model suggests a delay to mid-July to generate an additional $151,029 to the fishery.

The effect of the year 2000price differentials can be predicted from a model similar to Figure 6. This model incorporates ex-vessel price differentials to investigate a delay of the season opening. The overall values to the fishery are lower than the continuous models.

A delay in the season opening to the first of July over three seasons would generate as much as $377,574 per year to the fishery from growth and ex-vessel prices in equilibrium. The static models do not include the discounted values only equilibrium conditions.

Sensitivity analysis in the dynamic model is also subject to unknown natural mortality and ex-vessel price equations. Lower natural mortality rates allow the biomass to increase and generate increasing yield and revenue. Variation in the constraints on capacity in the fishery and fishing mortality rates have provided insight to the expected behavior of the fishery as a result of management constraints. When the fishing mortality is constrained to a lower level (e.g. .12/mo.) The fishery tends to distribute evenly within the season, preventing a pulse fishery. The higher the fishing mortality rate the more likely the biomass can be driven down within a month of fishing. The discount rate used in the dynamic model was an annual value of 0.05. However, sensitivity about the rate of time preference in the fishery may indicate the importance of timing in this fishery.



Figures 5 and 6. Seasonal multi-cohort revenue per recruit isopleths for *Pandalus jordani* using estimated ex-vessel price equations from 1994 (top) and price differentials from 2000 (bottom). Summer and winter natural mortality is .09 and .06.

5.0 DISCUSSION/FURTHER RESEARCH

Fishery managers at the Oregon Department of Fisheries and Wildlife (ODFW) focus on the minimum average size limit of 160 whole shrimp per pound as the primary management tool. Harvesters and processors can decide when, where, and how to fish for shrimp to best respond to the changing market. The management approach in Oregon allows significant flexibility. However, an additional measure to prevent recruitment overfishing may prove to be in the best interest of the fishery as a result of increased revenue from delaying harvest early in the season. The timing of this management measure will require additional research to determine the opportunity costs to the fleet as well as the potential economic value f of the delay.

The models presented provide biological and economic insight to the Pacific ocean shrimp fishery. Comparisons of the models indicate how a fishery management decision to delay the season opening to prevent biological growth and recruitment overfishing can compliment revenue objectives in the fishery. The models presented indicate a favorable response in yield and revenue as a result a decision to delay the fishery. Traditionally, price disputes between harvesters and processors have unofficially delayed the season opening due to strikes by the harvest sector. Just how much the models suggest the fishery to be delayed must be determined by investigating the economic opportunity costs to the fishery.

Further research will incorporate selectivity, recruitment, bycatch reduction devices and environmental conditions. In addition, cost information from processors and harvesters will be included to develop an economic yield per recruit model for this fishery to determine the tradeoffs as a result of management decisions. The completion of the bioeconomic analysis will require incorporating and evaluating multiple objectives for this fishery.

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