

# Optimization Model for the Oregon Ocean Shrimp Fishery

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**Abstract.** A bioeconomic model of the Oregon ocean shrimp (*Pandalus jordani*) fishery was developed to evaluate management policy options for maximizing fishery yield, revenue, and/or net present value using existing regulatory policy approaches. The base model accounts for a multiple cohort seasonal fishery, a count per pound catch composition, and an ex-vessel price relationship. The model chooses the fishing strategy by identifying the timing and intensity of fleet effort as the number of trips per month. Results of the base model indicate that optimizing yield requires early season harvest of age 1 recruits, whereas revenue and profit optimization suggest a delay in the season opening date. Two variations of the base model are presented: 1) heterogeneous vessel related opportunity costs, and 2) the integration of processing and harvesting sectors. Each variation compares management options relative to the base model.

Bioeconomic model, ocean shrimp, integrated fishery, optimal management

## 1. INTRODUCTION

The west coast ocean shrimp, *Pandalus jordani*, fishery is prosecuted from Morro Bay, California to Cape Beal, British Columbia. The Oregon coast is the center of distribution for ocean shrimp and has been the most consistent fishery since the 1950's. The Oregon fishery is composed of 150 vessels and 10 processing facilities. Vessels range from 40-60 feet in length with eighty five percent hauling double nets participating in a 7-month seasonal fishery from 1 April to 31 October. Seasonal shrimp landings range from a high of 48 million pounds in 1987 to a low of 6 million pounds in 1992 (ODFW, 1997). The fishery generates average annual revenues of \$17 million or approximately 20% of Oregon's fishery revenues. Ninety percent of the shrimp are cooked and peeled IQF (individually quick frozen) and sold to restaurants and retail outlets. Although many economic factors can influence ex-vessel prices, a key factor is the size of shrimp. Ex-vessel prices for shrimp are based on the count per pound (CPP) calculation from the landed catch. Shrimp with a CPP less than 140 receive \$0.15-\$0.25 more than smaller shrimp with a higher count. Wholesale prices range from \$3.00-\$4.50 per pound, depending on finished count.

The Oregon Department of Fish and Wildlife (ODFW) collects and maintains biological information on ocean shrimp, and conducts analysis on the status of the stock. ODFW focuses management on maximizing economic yield in the fishery consistent with maintaining the stock, and preventing growth and recruitment overfishing. Fishery managers rely on a combination of season closures, mesh size, and CPP regulations to manage the shrimp resource. The current regulation requires that average CPP not exceed 160 shrimp per pound (353 shrimp per kg) per trip. This regulation is intended to protect age one shrimp from overfishing and to improve economic benefits from the fishery (PFMC, 1981).

The optimization model in this research addresses management options for the fishery relative to alternative policy objectives. The base model maximizes fishery benefits by choosing the optimum timing and intensity of harvest each season. Yield, revenue, or profit maximization policy objectives generate different fishing strategies and result in diverse impacts on different sectors of the industry. The model addresses contemporary fishery management issues such as growth overfishing, recruitment overfishing, and market linkages including optimal timing of harvest.

## 2. BIOECONOMIC MODEL

The model consists of biological and economic mathematical equations to represent each component of the shrimp fishery. The relationships describing biological dynamics for shrimp follow the generalized age structured model and are equivalent to a discrete time optimal control problem (Clark, 1990). The time path of harvest is chosen to maximize a policy objective (yield, revenue, or net present value) subject to biological dynamics, economic conditions, and shrimp regulations. The time path is determined by allocating effort (trips)

across months within a season for a fishery of 110 vessels (Table 1). The economic component incorporates revenue and cost information obtained from the processing and marketing sectors. The regulatory component uses a weighted objective decision process to determine trade-offs in variable management schemes. Models optimizing yield, revenue, or net present value policy objectives were systematically generated for comparative purposes.

**Table 1. Mathematical Model Notations and Descriptions**

<b>Biological and Economic Parameters:</b>	
<i>q</i>	catchability coefficient (initially fixed)
<i>acpp</i>	monthly count per pound by age
<i>opc</i>	opportunity cost per vessel
<i>ni</i>	standing stock (shrimp numbers for ages 2, 3, and 4)
<i>ms</i>	instantaneous natural mortality April-October by age
<i>mw</i>	instantaneous natural mortality November-March by age
<b>Biological and Economic Variables:</b>	
<i>N</i>	number of shrimp (billions)
<i>Z</i>	instantaneous total mortality (TM)
<i>F</i>	instantaneous fishing mortality (FM)
<i>Y</i>	harvest yield in pounds (PDSL)
<i>EVP</i>	ex-vessel price
<i>PCPP</i>	count per pound mixture of age classes
<b>Indices:</b>	
<i>a</i>	age classes or cohorts (months) available for harvest
<i>y,s</i>	years (2000,2001...,2016) and season months beginning with larval release in March(Mar....Feb)
<i>sel</i>	selectivity
<i>avfc</i>	average fixed cost per vessel
<i>vtm</i>	vessel trips per month
<i>r</i>	annual real discount rate
<i>rec</i>	recruitment
<i>grth</i>	monthly weight at age
<i>NV</i>	number of vessels
<i>E</i>	effort - the control variable (IE)
<i>C</i>	harvest in numbers (catch)
<i>TPS</i>	trips
<i>WHS</i>	wholesale price
<i>v</i>	vessel types

## 2.1 Biological Component

To simplify the baseline analysis, shrimp recruitment was assumed constant at 5 billion 12 month old shrimp. This is within one standard deviation from the mean for the 17-year recruitment index (Hannah, 1999) and entered as a parameter, *rec*. Different seasonal natural mortality rates (*ms*) due to differential mortality caused by migrating juvenile hake during the spring and summer months (Hannah, 1995) and is modelled for winter (s = Nov. through Mar.) and summer seasons (s = Apr. through Oct.). Fishing mortality is proportional to the abundance of shrimp. The catchability coefficient, *q*, defined as the instantaneous rate of fishing mortality caused by a single unit of gear, which is derived from a 10 year average under an assumed level of elemental trawl efficiency of 50% (Hannah, 1995). A nonlinear selectivity factor (0.2 in April to 1.0 in July) for age 1 shrimp was multiplied by the fishing mortality rate. Shrimp weight at age was taken from monthly ODFW carapace length at age samples of the commercial catch. Hannah and Jones (1991) provide an allometric equation for the growth of ocean shrimp using a linear regression estimate of the length weight relationship (Zirges et. al., 1982). Seasonal mean shrimp CPP estimates were calculated from the average weight at age of observed shrimp. Historical catch and effort data (1980-1990) were used to establish the effort values corresponding to fleet size and activity (Hannah et al., 1997). Monthly effort, in the form of single rig equivalent hours per month (sre-h), ranged from 8,000 sre-h/month to over 20,000 sre-h/month. Shrimp trips consistently last 5 days and vessels can make as many as 3 trips per month. The model chooses the monthly level of trips (TPS) to optimize the policy objective over a 12 year time horizon.

## 2.2 Economic Component

Ex-vessel and wholesale price equations are based on the average weighted CPP estimates from green and finished count (FC) as the key quality factors in the determination of prices (Larkin and Sylvia, 1999). A linear functional relationship between average ex-vessel price and average CPP was estimated based on 14 years of historical sample data from ODFW and West coast landed ticket data (PACFIN). A linear relationship provided the best fit, accommodated dummy variables, and has the smallest risk of bias if misspecified. More comprehensive determinations on shrimp supply and demand equations can be found in Doll (1972), Ward and Sutinen (1994), and Funk et al., (1998). An hedonic price equation was used to identify the value of count per pound (Table 2). Dummy variables for yearly differences in ex-vessel price were used to represent the value of shifts in other annual supply and demand factors (Ethridge and Davis, 1982).

The general hedonic model is represented as:

$$EV_{y,s} = f(CPP_{y,s}, D_y) \quad (1)$$

where CPP corresponds to average weighted count per pound of shrimp in the green state, dummy variables are defined as:  $D_{y=14}$ ,  $D_{1=1}$  if 1986,  $D_{2=1}$  if 1987,.. $D_{14=1}$  if 1999, else 0; y represents years, and s represents months. The estimated equation indicates that a 100 count shrimp decrease results in \$0.15 increase in the real ex-vessel price per pound.

**Table 2. Results of Count per Pound (CPP) on Ex-Vessel and Wholesale Prices**

Variables	Ex-Vessel Prices $R^2 = 0.84$ n = 98	Wholesale Prices $R^2 = 0.80$ n = 1756
Intercept	0.63489	3.5349
CPP (Green state)	-0.00148**	
FC (Finished count)		-0.00297***
D1986	-0.1259***	
D1987	0.0039*	
D1988	-0.1715***	
D1989	-0.2156***	
D1990	-0.1379***	
D1991	-0.0367*	
D1992	-0.1939***	-0.1837***
D1993	-0.2288***	-0.3736***
D1994	0.0102*	0.1909***
D1995	0.1307***	1.0077***
D1996	0.0092*	0.5273***
D1997	-0.1163***	0.0284*
D1998	0.0275*	0.2713***
D1999	N/A	0.2786***
D2000	N/A	0.3666***

Prices (\$US per pound) are deflated by the producer price index for seafood commodities (January 2000 =100). Asterisks indicate significance at the 10 (\*), 5 (\*\*) and 1 (\*\*\*) % levels. Real (base 2000) ex-vessel price:

$$EV_{y,s} = .6349 - .0015 * (CPP), \text{ Wholesale prices (base 2000).}$$

The wholesale price estimation was estimated using weekly data collected from the Urner Barry Seafood Price Current from 1990-2001 by finished count (CPP) and compared with the survey results. Finished counts ranged from 175-250, 250-350 and 350-500 shrimp per pound and included both *P. jordani* and *P. borealis*. The majority of the data is from *P. borealis* which is considered a near perfect substitute and used as a proxy for *P. jordani* (Brokers, personal communication). A wholesale price function was estimated using finished CPP and dummy variables to address yearly effects.

$$WP_{y,s} = f(FC_{y,s}, D_y) \quad (2)$$

FC corresponds to average weighted count per pound of processed shrimp, dummy variables are defined as:  $D_{y=10}$ ,  $D_{1=1}$  if 1990,  $D_{2=1}$  if 1991,.. $D_{10=1}$  if 2001, else 0, y represents years, and s represents months. The estimated equation suggests that a 100 count decrease results in a \$0.30 per pound increase in the real wholesale price of shrimp.

The cost of a fishing trip was calculated using data from a 1998 survey covering a representative subsection of the fleet. The model assumes the variable cost of a fishing trip for an average 5-day trip with a skipper and two crew hauling two 85 foot nets (double rigged vessels). Variable costs for a fishing trip include fuel, crew share, supply and maintenance costs. Annual fixed costs were identified as that proportion of fixed costs attributed to shrimp.

**Table 3. Select Model Equations**

Count per pound:	$PCPP_{y,s} = (\sum_a B_{y,s,a} * ACPP_{s,a}) / \sum_a B_{y,s,a}$
Shrimp landings:	$PDSL_{y,s} = YLD_{y,s} * 2.2046$
Catch per unit effort:	$CPUE_{y,s} = PDSL_{y,s} / E_{y,s}$
Product Recovery Rate	$PRR_{y,s} = .4 - .0008 * CPP_{y,s}$
Green to Finished Count	$FC_{y,s} = CPP_{y,s} / PRR_{y,s}$
Revenue:	$REV_{y,s} = EVP_{y,s} * PDSL_{y,s}$
Variable costs by trip:	$FLC_{y,s} = 5 \text{ days} \cdot \$US \text{ price/gal}_{y,s} \cdot 250 \text{ gal/day}$ $SHC_{y,s} = REV_{y,s} \cdot .39$ $SUC = Food + ice$ $MC = unload \text{ fee} + avg. repair \text{ per trip}$
Monthly variable costs:	$VCST_{y,s} = FC_{y,s} + SHC_{y,s} + SUC + MC$
Total variable costs:	$TVC_{y,s} = TPS_{y,s} * VCST_{y,s}$
Total fixed costs:	$TFC_{y,s} = NV_{y,s} * AVFC$
Total seasonal cost:	$CST_{y,s} = TFC_{y,s} + TVC_{y,s}$
Objective functions:	$\text{Max TYLD} = \sum_y (1/(1+r)^y) * \sum_s (YLD_{y,s})$ $\text{Max TREV} = \sum_y (1/(1+r)^y) * \sum_s (TREV_{y,s})$ , $\text{Max NPV} = \sum_y [(1/(1+r)^y) * \sum_s (TR_{y,s} - CST_{y,s})]$

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Opportunity costs were identified as the amount of revenue per month the harvesters could obtain in alternative fisheries. The “heterogeneous vessel” extension to the base model describes the shrimp fishery as composed of part and full time vessels. Part time vessels have higher opportunity costs because they have permits and/or gear to participate in other fisheries. Full time vessels are shrimp specialists. These characteristics have been identified by vessel length and revenue by Radtke and Shannon (1998) in an overview of Oregon’s Commercial Fishing Fleet. For example they found that thirty one percent of the shrimp fleet also hold groundfish permits. It is these that are modeled as part time vessels. In the model, there are 30 part time and 80 full time vessels. The additional opportunity cost is attributed to part time vessels at \$3000/month, the revenue that part time vessels would receive in another fishery. Vessel costs can differ from vessel size, crew requirement, trip, and fixed costs. Full time vessels are characterized as those that harvest shrimp seven months of the shrimp season with no opportunity to participate in other fisheries.

The market-integrated extension for the ocean shrimp fishery incorporates both the harvesting and processing sectors. An integrated fishery model includes harvesting and processing costs and wholesale prices. The CCP estimates for landed product are used to determine processed output volume and revenue via the shrimp meat recoverable factor (PRR). The relationship between shrimp landed count (CPP) and processed count (FC) was developed based on processor interviews and industry size price differentials, reflecting the marketable finished count as a function of the count per pound of raw shrimp (PFMA, 2000). The market-integrated model optimizes discounted yield, revenue and NPV and compares the results against the results for the base model.

### 3.0 MODEL RESULTS AND EXTENSIONS

Three alternative policy objectives were evaluated for the base model and the two extensions. For each optimization the model selects the optimal season opening and number of trips. Output results for all nine runs including average monthly landings, revenue, profit, effort, and CPUE were recorded (Table 4). The objective for maximizing yield represents the shrimp yield in metric tons captured by the fishing fleet over a 12 year time

period. The objective for maximizing discounted revenue represents fleet revenue (\$US) in year 2000 dollars. The objective of maximizing NPV represents the net return to the shrimp fleet and the domestic value of the resource to society (Lee, et al., 2000). The base model, designed with constant recruitment, knife-edge selectivity, and homogenous vessels, selects the monthly level of effort over the twelve year time period. The present value of the objective function is calculated using an annual discount rate of 5%.

### 3.1 Base Model Results

The model that optimizes yield generates 77.7 thousand metric tons over the 12 year period. The value is equivalent to a seasonal 58.8 metric tons per vessel. Maximizing discounted revenue generates \$55.5 million over the time period. The revenue value is equivalent to \$42,045 per vessel. The discounted net returns for the NPV optimization model total \$24.3 million over the 12 year period. The net value is equivalent to average net revenues of

**Table 4. Model Results and Extensions of the Oregon Ocean Shrimp Fishery**

Model 12 year	Discounted Landings Season (metric tons) Opening	Discounted Revenue (\$x1000)	NPV (\$x1000)	CPUE (sre-hx1000)	Average Trips/Year
<b>Base Model</b>					
<b>Yield</b>	77708.3	52615.3	20060.7	176.2	1370 June
<b>Revenue</b>	77052.5	55473.8	22453.4	188.6	1308 July
<b>NPV</b>	68887.3	52731.0	24259.8	202.0	1041 July
<b>Heterogeneous Fleet</b>					
<b>Yield</b>	80864.7	70574.2	23162.4	177.3	2310
April					
<b>Revenue</b>	77922.2	72284.7	29154.9	224.0	1757 May
<b>NPV</b>	69413.2	68852.4	32199.6	326.2	1161 June
<b>Integrated Fishery</b>					
<b>Yield</b>	71513.1	79332.2	31287.3	272.5	1251 May
<b>Revenue</b>	68282.7	96334.4	48415.0	339.3	1102 June
<b>NPV</b>	61244.9	93253.8	50459.5	397.6	866 July

\$18,387 per vessel per year including fixed costs. A graphical representation of average seasonal effort (trips per month) by optimization policy is shown in Figure 1a. For the yield optimization model, serious fishing is initiated in June when effort increases to 315 trips per month. The model that optimizes revenue limits serious fishing until July at 275 trips per month which then increases to the maximum level of fishing (330 trips per month) by August. The model optimizing net present value delays serious trip effort until August when all vessels fish to their maximum at 330 trips per month.

The average season catch per unit effort (CPUE) for all optimization policies show an early season level from 230 to 280 pounds per sre-h. CPUE increases in mid season to 366 when yield is optimized, to 426 when revenue is optimized, and to 512 when NPV is optimized and decreases again in late season (Figure 1b). The early season CPUE reflects the low level of constant fishing. NPV is consistently 50 lbs. per sre-h greater than the CPUE under revenue optimization and increases to 150 lbs. per sre-h greater than the CPUE under yield optimization in the later months of the season. Average season landings by month (pounds x1000) by optimization policy are presented on the right hand axes of Figures 1c and 1d. The model that optimizes yield shows an average 5.6 million pounds in June and decreases to 2.9 million by September. Figure 1c shows the yield from the model that optimizes revenue as 5.5 million lbs. in July and August reducing to 3.3 by October. The NPV optimization model yields 7.2 million lbs. in August decreasing to 4.4 million lbs. by October.

Average monthly revenue and profit per season are presented in \$US (x1000) and reflect the seasonal landings pattern. The model that optimizes yield generates average revenues of \$2.4 million in June but decreases throughout the season (Figure 1c). The revenue optimization model generates \$2.45 million in revenue in July, \$2.5 million by August, and decreases to \$1.6 million by October. The NPV optimization model generates average revenues of \$3.4 million in August decreasing to \$2.1 million by October. The average monthly profit from the model that optimizes yield generates \$1.15 million in June and decreases as the season progresses (Figure 1d). The model that optimizes revenue generates \$1.2 million in July and August decreasing to \$650 thousand in October. The net present value optimization model generates \$1.7 million in August, decreasing to \$970 thousand by October.

### 3.2 Extension Heterogeneous Vessels

The heterogeneous extension model that optimizes yield generates a discounted 80.9 thousand metric tons over the 12 year period (Table 4). The value is equivalent to a seasonal 61.3 metric tons per vessel (part and full time). Discounted revenue optimization generates \$72.3 million over the twelve year time horizon. The revenue is equivalent to \$54,214 per vessel (part and full time). Discounted net returns for the NPV optimization total \$32.2 million over the time period. The net value is equivalent to average annual net revenues of \$30,411 for part time vessels and \$22,137 for full time vessels.

Seasonal average trips per month by vessel and optimization policy type are shown in Figure 2a. The model that optimizes yield shows maximum effort for part (30), and full time (80) vessels for the entire season. The revenue optimized model delays effort to May (at 7 part and 17 full time vessels) and exerts full effort by June. The model that optimizes NPV delays effort to June (at 3 part and 8 full time vessels); by July full effort is exerted for part time vessels while only 12 full time vessels fish 3 times per month. In August through October both vessel types fully participate in the fishery.

Seasonal average monthly profit for the heterogeneous models that optimize yield and revenue show a consistent 44 percent difference between full and part time vessels. Part and full time vessels in the yield optimization model generate average net monthly revenues of \$5359 and \$5209 in June, respectively (Figure 2b). The monthly net revenue decreases in August to \$3949 part time and \$3799 full time vessels. The model that optimizes revenue among vessel types generates average net monthly revenues of \$8135 for part time vessels and \$7985 in June. August net revenues for full \$5878, and part time \$5728 vessels show a decrease in net revenue. The model that optimizes NPV shows part time vessels generating \$14,101 in July while full time vessels generate \$1752. In August, average monthly profit for each vessel type is \$11,850 for part time and \$11,700 for full time vessels.

### 3.3 Extension Integrated Fishery

The integrated fishery extension shows discounted net returns for the model that optimizes NPV totaling \$50.4 million over a 12 year period. The net value is equivalent to average net revenues of \$4.2 million per year to the fishery (Table 3). Graphical representations of average shrimp landed versus average pounds of shrimp processed for each optimization policy are presented in Figure 3a. The model that optimizes yield attains the highest average monthly landings in June at 5.5 million pounds that are processed into 1.4 million pounds of marketable shrimp meat. The revenue optimization model generates a high season average of landed shrimp in August when 6.2 million pounds are landed and 1.7 million pounds processed. The model that optimizes NPV attains average high season landings by September when 5.6 million pounds of landed shrimp are captured and 1.6 million pounds of shrimp are processed.

Average season catch per unit effort for the integrated fishery is presented by optimization policy. Figure 3b shows the model that optimizes yield attains a high of 350 pounds of shrimp per sre-h in June and declines through the season. The revenue optimization model for the integrated fishery generates 440 pounds per sre-h in July and decreasing in August. The model that optimizes NPV reflects the 15 year average CPUE of 292 pounds per sre-h (Hannah et. al., 1997). The average CPUE values by season month generate 470 pounds per sre-h in July decreasing to 410 pounds per sre-h in August.

## 4. DISCUSSION

The optimization model and subsequent extensions provide biological and economic insight to the Pacific ocean shrimp fishery. Fishery managers at the Oregon Department of Fisheries and Wildlife (ODFW) presently focus on the minimum average size limit of 160 whole shrimp per pound as the primary management tool. The management approach in Oregon allows significant flexibility in objectives. Harvesters and processors can decide when, and how much shrimp to fish for in response to changing market conditions.

An optimization model was created to investigate the multiple objectives this fishery may attempt to achieve on a long term, sustainable basis. Base model results show annual net revenue estimates from \$17-20 million. Model results are consistent with the yield and revenue per recruit models developed by Gallagher et al., (in prep.). The model that optimizes yield reveals a fishing strategy that suggests utilizing the incoming year class of age 1 shrimp earlier in the season; conversely, optimizing NPV indicates delaying seasonal effort in order to take advantage of higher value shrimp later in the season.

Model extensions indicate how fishery modifications affect revenue and net present value objectives in the fishery. A realistic extension of the base model separates the fishery into full and part time vessels showing little difference in fishing strategy despite the changes in opportunity costs between vessel types. A notable difference occurs under the model that optimizes NPV. In this scenario part time vessels exceed full time vessels in average effort, revenue and profit in July switching back in August when full time vessels exceed part time vessels. The market-integrated extension models the fishery as though the processors and harvesters work in concert to optimize policy objectives. Net benefits for all optimization policies belong collectively to the harvest/processing sector.

The optimization model has room for improvement. Further research will include sensitivity analysis about biological and economic parameters, variable recruitment, bycatch reduction devices, and environmental conditions in light of the present shrimp fishery. Determination of the tradeoffs as a result of management decisions will also be evaluated by calculating policy tradeoff curves for alternative objectives.

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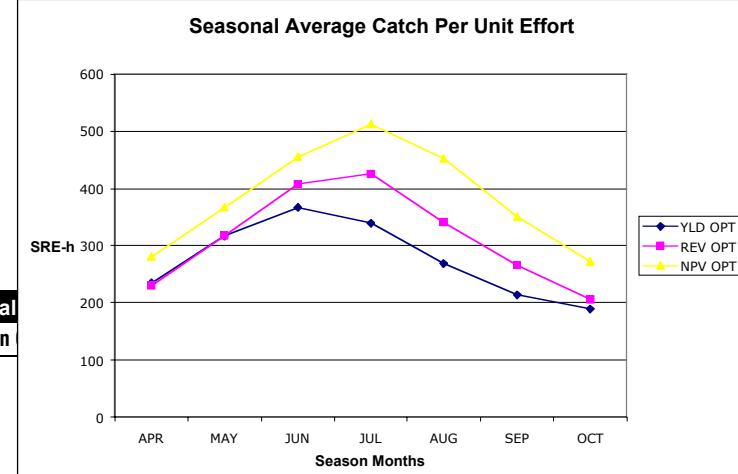
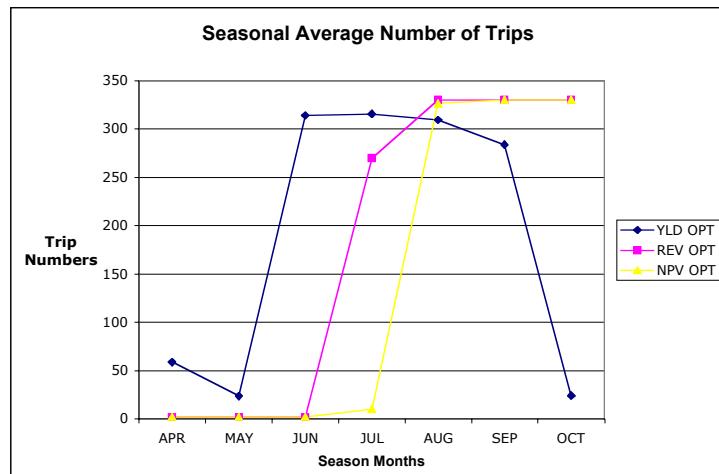


Figure 1a

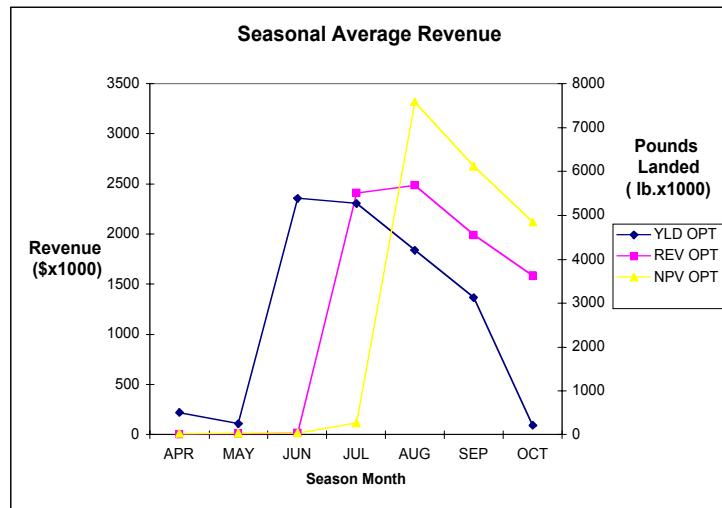


Figure 1b

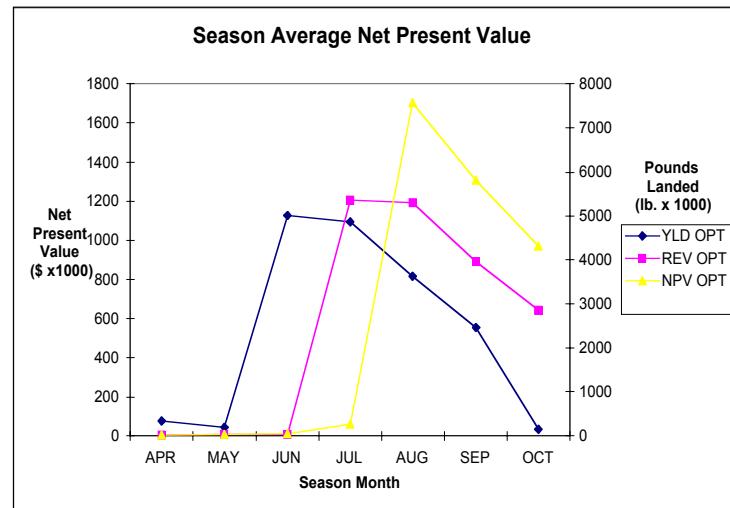


Figure 1c

Figure 1d

Figure 1. Graphical Representations of Average Base Model Seasonal Results  
a) Effort, b) CPUE, c) Revenue and Landings, d) Net Present Value and Landings

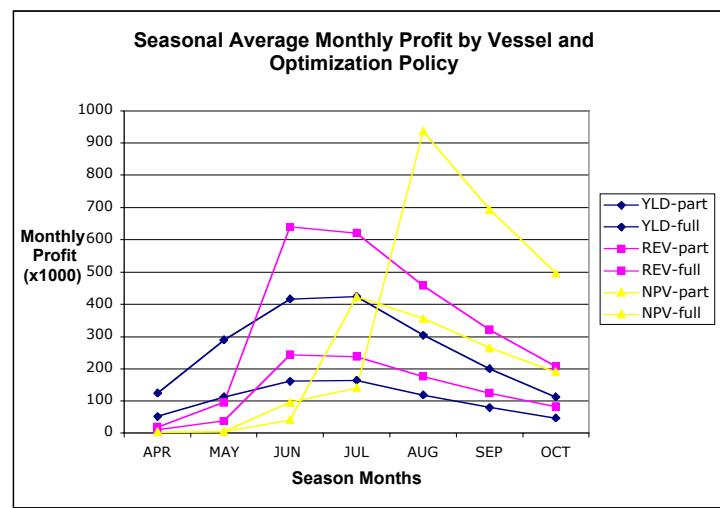
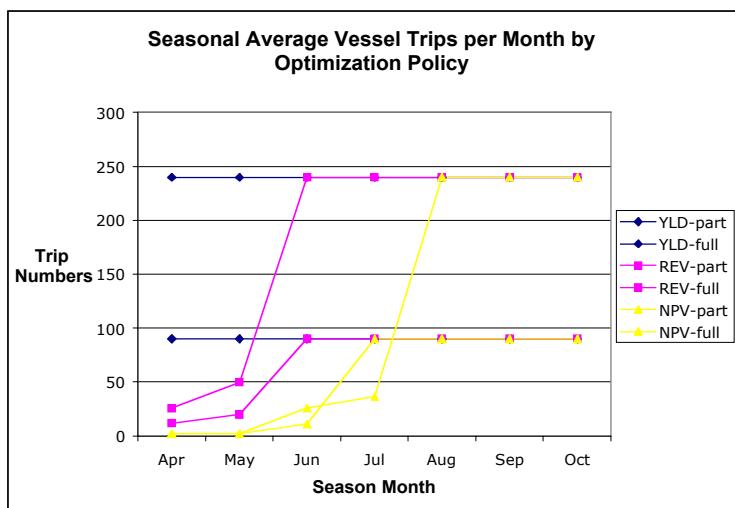


Figure 2. Graphical Representation of Average Heterogeneous Vessel Revenue Optimization by Vessel Type:  
a) Effort, b) Landings.

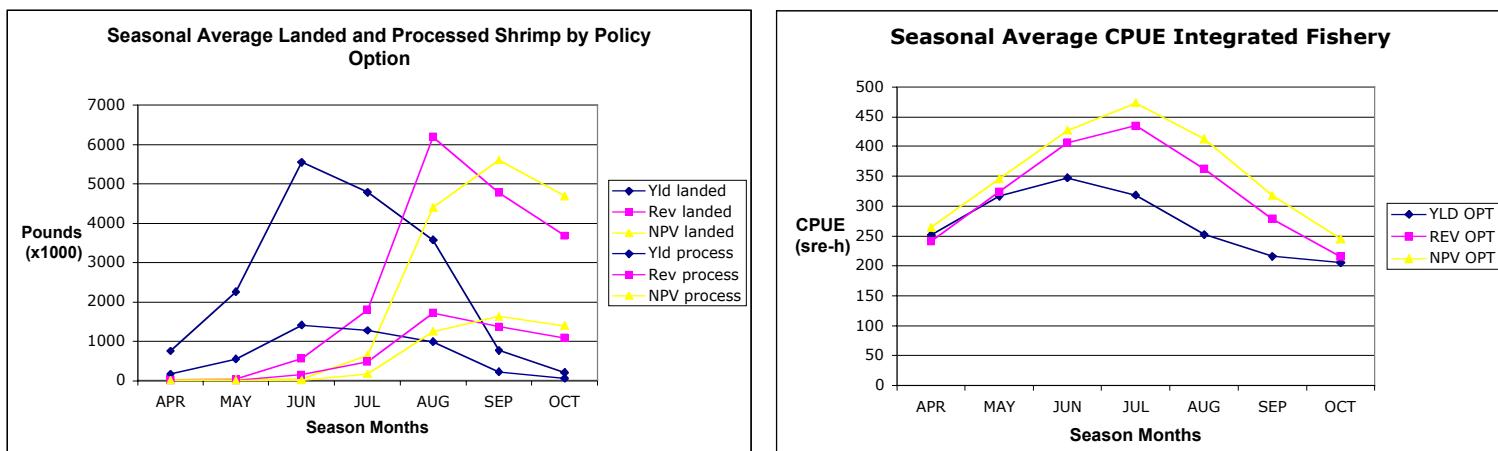


Figure 3. Graphical Representations of an Integrated Shrimp Fishery a) Landed and Processed Shrimp under Yield Optimization, b) Seasonal Average Catch Per Unit Effort by Optimization Type.