Oregon Dungeness Crab Fishery Bioeconomic Model: A Fishery Interactive Simulator Learning Tool
Final Report

Oregon Dungeness Crab Commission

Cover Photo Credit

Adult Dungeness crab grow about one inch every time they moult (shed their exoskeleton). A moult occurs up to six times per year for juvenile crab and once per year for most adult crab. Image courtesy of Scott Groth, Pink Shrimp/ South Coast Shellfish Project Leader, Marine Resources Program, Oregon Department Fish and Wildlife, December 2016.

Reproduction of Material

Suggested Citation

Davis, Shannon, Gil Sylvia, Noelle Yochum, and Chris Cusack. Oregon Dungeness Crab Fishery Bioeconomic Model: A Fishery Interactive Simulator Learning Tool. Prepared by OSU Coastal Oregon Marine Experiment Station and The Research Group, LLC for the Oregon Dungeness Crab Commission. March 2017.

Oregon Dungeness Crab Fishery Bioeconomic Model: A Fishery Interactive Simulator Learning Tool Final Report

Version 5.7

prepared by

Coastal Oregon Marine Experiment Station
Oregon State University

and

The Research Group, LLC
Corvallis, Oregon

prepared for

Oregon Dungeness Crab Commission

March 2017

(this page is intentionally left blank)

PREFACE

The authors' affiliation for model development and programming were:

- Gil Sylvia, Marine Resource Economist and Director OSU Coastal Oregon Marine Experiment Station
- Shannon Davis, Principal, The Research Group, LLC Corvallis, Oregon
- Noelle Yochum, Ph.D. and Chris Cusack, Ph.D. while they were students at OSU

The project corresponding author is Dr. Gil Sylvia and can be reached at gil.sylvia@oregonstate.edu or (541) 867- 0284.

The project was sponsored by the Oregon Dungeness Crab Commission (ODCC). A 14-member study steering committee met five times during the course of the project. The members (and representation) are:

John Corbin, Chair (Commissioner, harvester)	Jake Postlewait (Commissioner, public)
Crystal Adams (Commissioner, processor)	Hugh Link (Commission staff)
Dave Wright (Commissioner, processor)	Al Pazar (harvester and processor)
Mike Retherford (Commissioner, harvester)	Cody Chase (harvester and direct sales)
Rick Lilienthal (Commissioner, harvester)	Jen Wimpress (FISHCRED staff)
Brian Nolte (Commissioner, harvester)	Bob Eder (harvester)
Nick Edwards (Commissioner, harvester)	Caren Braby and Kelly Corbett (agency)

Industry testimony during steering committee meetings was extremely important in shaping model development. Justin Yeager (harvester) regularly attended steering committee meetings and shared useful fishery information. Hugh Link, Executive Director ODCC, was especially helpful in discussing fishery practices and management issues. Caren Braby and Kelly Corbett from Oregon Department of Fish and Wildlife (ODFW) provided valuable guidance and insight on research and management issues. Harvesters and processors who participated in the cost-earnings survey interviews should be recognized for taking time to explain their operations, costs, and management views. Finally, we thank five anonymous model beta testers. Their comments about methods and features led to needed model improvements.

The ODCC is the owner of an operational copy of the Excel file containing the model. The contact for requesting a copy is Hugh Link, Executive Director at hugh@oregondungeness.org or (541) 267-5810. Procurement of a copy is single user permission and further distribution is not authorized. The programming code is owned by Oregon State University, Office of Commercialization and Corporate Development (OCCD). If there is interest in commercial use or in obtaining code for modification, contact Joseph Christison, Intellectual Property and Licensing Manager joseph.christison@oregonstate.edu (541) 737-9016.

The project authors and not the sponsors were responsible for generating project results. The authors do not make any warranties with respect to the project including fitness for any particular purpose. In no event shall the authors assume any liability for use of the program or derived information and shall not be responsible for any direct, indirect, or consequential damages that might arise from the application.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

Tables and Figures

TABLE OF CONTENTS (CONT.)

Appendix

GLOSSARY

Base period, current year, and following year are time references for datasets containing weekly data and weekly model results. The base period dataset contains weekly averages across seven seasons (2007-08 through 2013-14) for actual effort and harvest fishery measures. The current year and following year datasets contain modeled results for status quo and action. Status quo contains defaults for management, i.e. no change in vessel participation, no delay in season opening, and no early closure. The following year for the status quo dataset by definition would be zeros. For the action dataset, there is a current year and following year. The following year modeled results are from the analysis of carryover biomass being made available to the fishery. The difference between the status quo and action (net impacts) is added to the base period to generate absolute measures (gross impacts). Using the difference to generate a simulated season will tend to cancel modeling biases.

Biomass is mature male sublegal size and legal size Dungeness crab resource measured in either pounds or numbers of crab. It is assumed the sublegal size crab are pre-fishery recruits that will become legal size in the following year.

Carryover biomass is the current season avoided catch and handling mortality, less natural mortality and plus post-moult growth that is available to the fishery in the following season.

Catch is the amount of retained crab sold at a delivery. The data sources for catch per delivery are both logbooks and fish tickets. The logbook hailed catch (estimated by skipper) has been adjusted by ODFW to better pattern delivery tabulated catch. Catch can be purchased by either processors or the public in the case when vessel owners make direct sales.

Catch per unit effort (CPUE) is an aggregate productivity measure. Whenever used, the denominator (such as trips or net gear tow hours) needs to be defined. The statistic is useful when comparing current fishing productivity to a previous fishing event or to an overall average. It is sometimes used as a proxy for stock density after standardizing for catchability influencing factors, such as fish aggregation and gear selectivity. CPUE is not necessarily a valid measure across time because regulation, technology and other factors will change harvesting efficiency. For recreational angling, the multiplicative inverse is often used which is angler success rates, i.e. how many fishing days did it take to catch a fish.

Computer terms:

i. A "program" is a collection of instructions understood by a computer. The instructions are devised to assist a user develop an application requiring sophisticated calculations.
ii. A "program run" is the process of changing instructions and generating model results. Model outputs can be printed and set aside for future reference.
iii. A "dashboard" is a collection of common model input variables contained on an operation page that can be modified by the user.

Delivery is a processor purchase of harvests from a vessel after it returns to port or when vessels make direct sales to the public. The source for delivery counts is fish ticket data. There are rare occurrences that a vessel sells to more than one processor following a trip.

Discards are Dungeness crab of any gender, any size, and any condition (live, dead, or live but estimated to be killed as a result of handling) thrown overboard.

Dollar values (prices, revenues, costs, economic impacts, etc.) are expressed in 2014 dollars. The dollar adjustment uses the GDP implicit price deflator developed by the U.S. Bureau of Economic Analysis. The discount rate for the following season is assumed to be zero.

Economic contribution and **regional economic impact** (REI) are slightly different concepts, but in this report the two terms are used interchangeably. A stricter use of the term "contribution" would be for an economic activity that already exists. The use of the term "impact" would be when an economic activity is to be subtracted or added. REI is defined as the share of the regional economy supported by the expenditures made by the industry being analyzed. It can be expressed in terms of a variety of economic metrics, including personal income, equivalent jobs, business output, product added value, and taxes generated. Economic contribution estimates include the "multiplier effect" that represents the share of business activities from suppliers, provisioners, and services that sell to the harvesting and processing sector. It also includes the "induced effect" from respending generated income within an economic region. The economic level for showing economic contributions adopted for this report is the State level. The economic contribution at the community economic level is less than for the State because of trade leakage to a more diversified economic level.

The terms **economic analysis** and **financial analysis** are used interchangeably in this report, but economists actually have a stricter definition of the two terms. Economic analysis measures costs as "opportunity costs," which reflect their relative value (in their next best use) from an economy-wide framework. Financial analysis is a firm level measurement.

Effort is pot-pulls in a unit of time. The selected unit of time is a trip.

Exogenous and **endogenous** variables. Exogenous variable values are supplied to the model externally as contrasted with endogenous variable values that are the result of internal model calculations. For example, in the case where there is limited product substitution, a dynamic bioeconomic model may include price as an endogenous variable where the product value has an inverse demand relationship with catch.

An **exclusive economic zone** (EEZ) is a sea zone prescribed by the United Nations Convention on the Law of the Sea over which a country has special rights regarding the exploration and use of marine resources, including energy production from water and wind. The U.S. EEZ extends no more than 200 nautical miles from the territorial sea baseline and is adjacent to the 12 nautical mile U.S. territorial sea. For application by the Magnuson-Stevens Fishery Conservation and Management Act, the EEZ is defined as having an inner boundary that is coterminous with the seaward (or outer) boundary of each of the coastal states territorial sea. For West Coast states, the inner limit is coterminous at three nautical miles.

Fishery **engagement** is the proportion of participation in the Oregon Dungeness crab fishery in a given port (as measured by a variety of indicators including vessel counts and landing amounts) compared to all onshore landed fisheries in the state. Fishery **dependency** is the proportion of participation in the Dungeness crab fishery at a single port as compared to all onshore landed fisheries at the port.

First-purchasers are businesses (processors, buying stations, bait dealers, vessels selling to the public, etc.) that purchase from harvesters.

Fishery Economic Assessment Model (FEAM) is used to calculate fishing industry economic contributions. The FEAM is a derivative of the IMPLAN input/output model. The FEAM was originally developed by Hans Radtke and William Jensen for a project sponsored by the West Coast Fisheries Development Foundation in 1988. The FEAM has been continuously maintained for Oregon fisheries with the most recent iteration described in TRG (2015). The IMpact Analysis for PLANning (IMPLAN) is a software and dataset system for input-output models applicable to the nation, states, and counties. Datasets for U.S. zip codes are also available. IMPLAN is maintained by the IMPLAN Group, LLC (formerly MIG, Inc.) located in Huntersville, North Carolina.

Fishing intensity is a term that can have different definitions depending on its computational usage. For this project, it is defined as catch per unit area and per unit time. The more complex spatial and temporal structure definitions include exploitation rate and equivalent annual fishing mortality rate. Other measures of fishing intensity are in terms of the potential long-term effect on the stock.

Fishery management measures include four general types: **input** controls, **output** controls, **fees and taxes**, and **technical** (OECD 1997). Input control examples include license numbers, gear, area fished, and time fished. Input controls are considered to be an indirect means of limiting the exploitation of fish stocks because they do not directly control the amount of catch. Technical management measures are a subset of input controls. Examples include limits on fish size and sex, and limits on areas fished. Input controls often result in operational inefficiencies and variable catch. Output controls include management measures that directly limit catch (fleetwide and per vessel through trip limits or individual transferable quotas) and hence a significant component of fishing mortality (which also includes mortality from bycatch, ghost fishing, and habitat degradation due to fishing). Fees and taxes have resulted in only limited success to control harvests. With few exceptions, the application of fees and taxes in fisheries has been primarily intended as a source of revenue to offset administrative, management, and enforcement costs and to fund product marketing activities.

Harvest control rules (HCR) are the operational component of a harvest strategy, essentially are pre- agreed guidelines that determine how much fishing can take place, based on indicators of the targeted stock's status. HCR's are triggered by reference points that are measurable criteria which represent the state of a fishery. When the population drops below the reference point, the pre-agreed management responses take place.

Compensatory harvester revenue opportunity is a ratio of harvester Dungeness crab fishery revenue divided by the harvester's total annual revenue that includes any non-Dungeness crab fisheries revenue. A decrease in the ratio would be an indication that compensating revenue from other fisheries is needed to maintain total annual revenue.

Harvest value is catch times delivery price and is synonymous with ex-vessel value. **Wholesale value** is processor finish product weight times price paid by distributors. Sometimes inventory and transportation costs are included in the wholesale value, but in some arrangements a wholesale/distributor will assume the costs. Pre-retail supply chain arrangements can be complicated with several intermediaries such as exporting agents, re-processors, warehousing businesses, transporters, etc. having custody of the product. Or a processor may act as the distributor with sales directly to food service and retail vendors. The wholesale value used in the study analysis assumes an average price at a pre-distributor node in the supply chain across the many arrangements. The study analysis does not include economic impacts beyond the processor in the supply chain.

Management strategy evaluation (MSE) is a simulation-based, analytical framework used to evaluate the performance of multiple harvest strategies relative to the pre-specified management objectives (Pew 2016).

Marginal costs are expenditures related to undertaking the effort, such as gear maintenance, crew shares, bait, and fuel. These expenses are distinguished from fixed costs, such as moorage, insurance, and vessel repairs that would be incurred even if there was no effort.

Oregon Department of Fish and Wildlife (ODFW) is the Oregon state agency responsible for Dungeness crab management.

Pacific Fisheries Information Network (PacFIN) is the program name for a collaboration between member state and federal fishery agencies that supply the information needed to effectively manage fish stocks on the west coast of the United States. The member states are Washington, Oregon and California. Federal member agencies include NMFS and PFMC. The fishery data is stored, processed and disseminated by PacFIN staff. The PSMFC administers the PacFIN program.

Pacific Fishery Management Council (PFMC) is a U.S. federal board which oversees management of marine fisheries in EEZ waters off Washington, Oregon and California. It is headquartered in Portland, Oregon. The Dungeness crab fishery does not have a PFMC fishery management plan. Dungeness crab is managed by the three states through the Magnuson-Stevens Act Section 306(a) authorization, memorandum of understanding between the states, agreement with PSMFC for coordination and pre-season testing protocols, and federal authorizing legislation. The three states have jurisdiction over their respective permit holders and permit conditions (such as gear, seasons, etc.) as well as control over conditions for making landings within a state.

Pacific States Marine Fisheries Commission (PSMFC) was authorized by Congress in 1947 and is one of three interstate commissions dedicated to resolving fishery issues. The PSMFC is an interstate compact agency that helps state resource agencies and the fishing industry sustainably manage Pacific Ocean resources in the five-state region of Washington, Oregon, California, Idaho, and Alaska. Each state is represented by three commissioners. The Washington, Oregon, and California Dungeness crab fishery regulatory issues that affect more than one state's fishery are considered in a Tri-State Management Program process.

Crab pot is hatbox-shaped steel frame covered with webbed wire. The crab pot has restricted entry and exit openings so that only crab of minimum size are retained.

Pot-pulls are the number of pots retrieved in one or more strings during a trip.

Profitability is the difference between harvest value and costs for the Dungeness crab fishery. It is an indicator of financial change and should not be confused with a contribution to net income for the owner. Net income would be calculated after allocated fixed costs are subtracted from profitability. Distinguishing items to be included in fixed costs and how fixed costs are allocated to a particular fishery is a firm level decision. Determining common representation of fixed costs across all participants in a fishery is problematic (Terry et al. 1996).

Ratio references use effort in a context to show fishing effectiveness. The ratio's denominator would be fishing business inputs and outputs, such as a vessel's maximum permitted pots, catch, marginal costs, etc. An often used reference is CPUE, e.g. crab pounds retained per pot-pull.

Fishery **recruitment** is when a male crab reaches the certain size when it can be legally retained.

Season week is the consecutive week number defined to be 1 for the week the season started. Here are approximate calendar dates for a typical season that starts on December 1.

Week	Date	Week	Date	Week	Date	Week	Date
1	Dec. 1	11	Feb. 9	21	Apr. 20	31	Jun. 29
2	Dec. 8	12	Feb. 16	22	Apr. 27	32	Jul. 6
3	Dec. 15	13	Feb. 23	23	May 4	33	Jul. 13
4	Dec. 22	14	Mar. 2	24	May 11	34	Jul. 20
5	Dec. 29	15	Mar. 9	25	May 18	35	Jul. 27
6	Jan. 5	16	Mar. 16	26	May 25	36	Aug. 3
7	Jan. 12	17	Mar. 23	27	Jun. 1	37	Aug. 10
8	Jan. 19	18	Mar. 30	28	Jun. 8		
9	Jan. 26	19	Apr. 6	29	Jun. 15		
10	Feb. 2	20	Apr. 13	30	Jun. 22		

Effort for the **status quo and action** model stages is predicted using the weekly regression coefficients developed over the base period seasons. Model relationships are then used to derive catch and other metrics. The status quo stage has defaults for management and the action stage has the effects from user controlled management specifications. The weekly difference between the effects for status quo and action stages are applied to the base period to show the changes brought about by user inputs.

Trip is a vessel harvesting event. A single trip may be multiple calendar days. The source for trip numbers is logbook data which provides counts for unique vessel days. The accumulation of unique vessels days in a week is adjusted for delivery counts to account for multiple trip days.

Variable used in this report refers to the representation of a value in a statistical relationship. A **dependent variable** value is generated from a **function** containing other **independent variables**. The values for independent variables can be either supplied **exogenously** by the model user or supplied **endogenously** by a previous intermediary model calculation. Constants are generally needed to define the inherent relationship between the dependent variable and set of independent variables. The constants can be multiplicative with the independent variables or be additive in the equation. When multiplicative, the constants can be referenced as coefficients. Sometimes constants are referenced as **parameters**.

Value added at the processing sector level is equivalent to sales revenue less purchases of fish (including shrinkage at the processor level) and any services associated with the purchase of fish. Value added includes taxes and fees paid to government.

Crab **weight** and **count** require a conversion relationship. Handling mortality from ride-along survey data provided by Yochum et al. (2017) was count and carapace width, but other population dynamic modeling components such as harvests from fish ticket information are in pounds. Conversion relied on research from McCabe et al. (1987) that provided the estimating equation $\log10(g)=-3.54+2.86*\log10(cw)$ where g is grams and carapace width is millimeters. For example, a legal size crab 6.25 inch carapace width is 1.25 pounds.

ABSTRACT

Dungeness crab (*Cancer magister*) is usually Oregon's most valuable fishery (e.g. eight out of the last 10 crab season and other fisheries calendar year harvests), yet it is not managed explicitly for sustainable yields. Stock assessments are not used to determine annual exploitation levels. Without the impetus for optimal yield management policies or other alternative policy objectives, there has been little research work on developing bioeconomic models to help determine the "best" management practices. This study was designed to develop a management-level bioeconomic model to explore the economic impacts of alternative management practices consistent with stock conservation approaches.

Instead of quota based ocean commercial fishery management, state management is based on input controls for limited entry, pot gear limits, and a 3-S harvest strategy (size minimum 6 ¼ inch carapace width, sex male, and season start and duration). The traditional season start is December 1 (if meat yield and crab quality meet standards) and ends on August 14. A result of gaining Marine Stewardship Council certification for the Oregon fishery in 2010 (which was allowed to expire in 2015) was adoption of a generational harvest control rule reference point. This control rule "triggers" "adaptive management actions" if the fishery displays a four-year decreasing inter-season landing trend coupled to threshold landing and CPUE levels.

Dungeness crab moulting (when shells are soft) begins in the spring and peaks during summer months. There is no market for soft-shell crab and they are discarded. A recent study sponsored by the Oregon Dungeness Crab Commission (the same organization sponsoring this bioeconomic analysis) provided new information about soft and hard shell handling mortality rates. State management offers some protection for minimizing soft-shell crab mortalities through output controls. There is a participant weekly 1,200 pound trip limit starting the second week in June and harvests in the summer (June through August) cannot exceed 10 percent of season harvests in winter and spring (December through May). One of the drivers for developing the bioeconomic model was interest on the part of the fishing industry to determine the economic impacts associated with additional measures for protecting soft-shell crab, especially via earlier season closures.

Given the many assumptions that had to be used to parametrize the bioeconomic model, an interactive model was developed in Microsoft Excel software. A user can modify assumptions and investigate management actions relative to a status quo. Model metrics include harvest pounds, harvest value (ex-vessel revenue), harvester profitability (ex-vessel revenue minus trip variable costs), wholesale value, processor value added, community economic impacts, and changes to handling mortality numbers. These metrics were shown intra-season (weekly) and for each season. Tradeoff curves compared financial profitability versus indexes for conservation (changed fishing mortality), equity (changed trips), community economic impacts (changed personal income including multipliers), and compensatory harvester revenue opportunities (indicator that other fisheries revenue is needed to maintain total harvester annual revenue levels).

A production function was used to predict effort E_t (data is from mandatory logbook program) using participant behavior variables (fishing power, revenue per unit effort, continuous time,

other fisheries revenue opportunity, and catch riskiness). Linear programming was used to solve for catchability q_t in a population dynamics equation approach. Another recent study (again sponsored by the Oregon Dungeness Crab Commission) provided initial conditions for the mature male biomass B_t sublegal (one-year pre-recruitment) and legal size crab. The solution constraint is predicted catch ($q_tE_tB_t$) could not differ from actual catch (fish ticket data) by an error-factor in every week over a base period (seven seasons, 2007-08 through 2013-14). Manual tuning seasonal pre-recruitment is used to reduce catch divergence.

The model framework is to calculate the difference between a one-season simulated status quo alternative and a two-season management action alternative. The action alternative is for a current season and one following season. The following season is for the fishery utilizing the conserved biomass (if any) from the current season. The carryover biomass is any saved pre-recruit and legal size crab less its natural mortality plus an individual's growth during the current season. Effects from additional years' carryover biomass is minimal due to high natural mortality (adult instantaneous rate 1.25 per year) and high fishing mortality (51 to 92 percent exploitation rate legal size crab).

Results showed there were not significant economic benefits associated with reducing the season length. There would be a slight increase in overall fleet profitability for a couple of weeks early closure (0.1 percent at two weeks), then economic benefits dramatically decrease for earlier season closures. For example, an eight-week early closure management action resulted in losses of $214 thousand in harvest value, $79 thousand in profitability, and $301 thousand personal income to the State's economy. There were winners and losers among the fleet sectors for most management actions. For example, the "summer type" vessel class had a decrease in $186 thousand profitability while all other vessel classes increased profitability by $107 thousand. The tradeoff in conservation was a seasonal 1.8 percent reduction in fishing mortality (which includes a 69 percent decrease in handling mortality) and a 0.4 percent reduction in profitability. Natural mortality overwhelms handling mortality and any savings that might be gained by soft-shell management protection is offset by loss of biomass due to natural mortality. For example, the eight-week early closure results in 231 thousand pounds saved in handling mortality which compares to pre-recruit and legal male natural mortality of 12.7 million pounds during the same period.

The study makes multiple recommendations for additional science and fishery related research as well as suggestions for improving the model's performance to determine long-term harvest sustainability and optimum management practices. Developing the bioeconomic model fulfilled the purpose of providing a tool to inform decision making about changes to fishery management policies. A key benefit of using the tool is raising awareness of economic impacts when formulating policies. Having the economic impact information readily available can help foster improved collaborative relationships among stakeholders for managing the fishery.

EXECUTIVE SUMMARY

Oregon's commercial ocean Dungeness crab fishery is usually the state's most valuable fishery. The fishery's harvest value was highest eight times out of the last 10 years ending in 2016 using a crab season and other fisheries calendar year harvests for comparison. During this study's adopted base period (seven seasons 2007-08 through 2013-14) landings averaged about one-third of all the onshore harvest value. The base period average per season landings were 16.7 million pounds with a harvest value of $43.9 million. Annual catch was variable at +/- 39 percent during the base period. Vessel participation during the base period averaged 321 vessels. A few vessels participate in a commercial bay fishery in the fall after the ocean season is closed. There is also an active recreational crab fishery that takes place both in estuaries and the ocean. Dungeness crab is considered an iconic retail product and many Oregon Coast visitors have expectations for it being available year around as a locally caught fresh seafood restaurant menu and store item.

Despite the fishery's economic importance, there are many gaps in our scientific understanding that limit our ability to model the economic impacts associated with management actions that address conservation concerns or other management objectives. An impetus for developing such a model is managers and industry interest in knowing the economic impacts for closing the season early to avoid soft-shell crab handling mortality. The crab moulting process that causes the soft-shell condition begins in the spring and peaks during the summer months in Oregon. Soft-shell crab is not marketable and is discarded. The soft-shell crab discard mortality will subtract from future years harvestable biomass.

A deterministic bioeconomic model was developed to simulate the fishery in order to test potential management actions in general and specifically for the soft-shell crab conservation concern. The model development project is sponsored by the Oregon Dungeness Crab Commission. The Commission appointed a steering committee to oversee development of the model.

The economic side of the model relied on an effort production function with five independent variables related to a fisherman economic behavior:

1) A proxy variable for fishing power based on the number of participating vessels.
2) An indicator variable for catch per unit effort was combined with price to represent revenue per unit effort and utilized as a one week lagged "information" variable.
3) The continuous time variable was transformed to the power of 1.5 to account for any non-linear effort influences across the season.
4) The ratio of a vessel's Dungeness crab fishery revenue to a vessel's total revenue was used to capture intra-season fishery exit choice behavior.
5) Riskiness was defined to be the variance in vessel landings.

The biological side of the model relied on tracking population dynamics that accounted for fishing mortality, natural mortality, and recruitment. Fishing mortality was the addition of catch and handling mortality. Catch was predicted using a time variant catchability coefficient, fishing effort, and biomass. A linear programing solution was used to determine intra-season catchability and biomass. Solving is advantaged by using priors for initial conditions from a previous Oregon Dungeness Crab Commission (ODCC) sponsored study. Biomass was itemized for mature male sublegal size (one-year pre-recruit) and male legal size crab cohorts. Handling mortalities per retained catch were derived from a recently completed discard mortality rate study sponsored by the ODCC. The instantaneous rates for natural mortality were based on a detailed literature review. It was assumed that crab immigration and emigration biomass netted to zero.

The population dynamics model used a weekly structure in order to best represent fishing intensity and changes in the crab life cycle including moulting. Discard mortality rates are highest during the moulting period at the end of the season. Fishing intensity is highest at the start of the season. Sublegal soft-shell crab ultimately graduate into a recruited crab class by December 1. Natural mortality during and after the end of the fishing season is an adult instantaneous rate of 1.25 per year. A post-moult growth rate was applied to the biomass that contributed to the following season catch.

The ocean crab fishery is state managed. It is limited entry starting with the 1995-96 season. There are limits on pots per vessel categorized by three tiers (200, 300, and 500) that were originally assigned to vessel permits for the 2006-07 season depending on catch history. Resource conservation is attained by using a "3-S" management strategy for size minimum 6 ¼ inch carapace width, sex male, and season start and duration. The traditional season start is December 1 (if meat yield and crab quality meet standards) and ends on August 14. A result of gaining Marine Stewardship Council certification for the Oregon fishery in 2010 (which was allowed to expire in 2015) was to adopt a generational harvest control rule reference point. A four-year decreasing inter-season landing trend coupled to threshold landing and CPUE levels triggers development of adaptive management actions.

The existing season ending date serves as a compromise to allow for some summer deliveries and still protect against soft-shell crab handling mortality. There are two additional soft-shell crab protection provisions: cumulative weekly trip limit of 1,200 pounds starting the second Monday in June, and early season closure if the summer (June through August) catch exceeds the winter and spring (December through May) catch by 10 percent.

The bioeconomic model is developed in Microsoft Excel software and allows a user to change inputs and concurrently view results from those changes. Many assumptions were made in the model development, and user controls conveniently available on dashboards allow testing result sensitivity from modifying the assumptions. Real-time calculations of the effects are shown on graphs and tables adjacent to the user controls. A computer file ready for launching in Excel software is available from the project sponsor.

Changing model assumptions and management options creates biological effects that are tracked for the current season and one following season. The following season uses the conserved biomass from the current season. Any saved sublegal and legal size crab less its natural mortality plus post-moult growth during the current season would be the biomass subject to harvesting in the following season. The carryover biomass is not tracked in additional seasons because it is very small due to natural and fishing mortality during the one following season. Any potential reproduction in future years is also not tracked.

Developing the bioeconomic model for the purpose of analyzing early season closures also allowed for testing other management actions. The model is designed to provide evaluation of the following policies (singularly or in combination):

- Altering effort.
- Delaying season opening.
- Closing the season early.

Caution is suggested against relying on model results as a completely accurate or precise representation for altered effort or a delayed season start management changes. The possible response and adaptation of industry to these changes is not necessarily captured in the underlying sub-models and datasets.

The model structure computes the differences between a simulated status quo case and the new fishery situation arising from user controls. These are the net impacts. Gross impacts representing a total fishery measurement are calculated by adding or subtracting the difference from the base period situation. The displayed metrics include: pounds, harvest value (ex-vessel revenue), harvester profitability (ex-vessel revenue minus trip variable costs), wholesale value, processor value added, community economic impacts, and handling mortality. The community economic impacts are measured by changes to household income and job equivalents. The impacts include economic "multiplier" effects. Model outputs are intra-season (weekly) and are summed for a whole season. Tradeoff curves are generated to illustrate relationships of profitability relative to indexes representing conservation, equity, community economic impacts, and compensatory harvester revenue opportunities.

A five-vessel classification scheme was adopted for the study in order to improve model accuracy and better understand model results (Figure ES.1). The classification scheme was especially valuable for comparing and contrasting how the management actions affect each sub-sector of the fleet.

The following four sets of management scenarios provide examples of the usefulness of the model for analyzing alternative management actions alone or in combination with changes in other model economic and biological assumptions.

1) The main purpose for developing the model was to explore potential effects from early closure to avoid discard mortality on soft-shell crabs. Results showed there were not significant economic benefits associated with reducing the season length. There would be a slight increase in overall fleet profitability for a couple of weeks early closure (0.1 percent at two weeks), then economic benefits dramatically decrease for earlier season closures. An example eight-week early closure management option is shown intra-season (weekly) on Figure ES.2 and seasonally on Table ES.1 and ES.2. The seasonal economic impacts are a negative $214 thousand harvest value and negative $79 thousand profitability compared to the status quo case. The results also show there are different effects for each fleet sector creating "winners and losers" (Figure ES.3). The summer type vessel class demonstrated a decrease of $186 thousand in profitability while all other

vessel classes increased profitability by a combined total of $107 thousand. The tradeoff in conservation (defined as reduced fishing mortality) and fleetwide profitability is shown on Figure ES.4. The eight-week early closure resulted in a seasonal 1.8 percent reduction in fishing mortality (includes a 69 percent decrease in handling mortality) and a 0.4 percent reduction in profitability. The eight-week early closure economic impacts are negative $301 thousand personal income to the State's economy. The economic impacts represent impacts on harvesters and processors and do not include the effects on retail operations for any product forms including the locally caught, whole cooked, fresh product that is popular during the Oregon Coast summer visitor season.

2) The model can assess the economic effects due to combinations of changing environmental conditions and changing fishing intensity. For example, if the moult occurred two weeks and four weeks earlier and there was a 10 percent decrease in season effort, the change to profitability would be a negative 3.8 percent and a negative 5.3 percent respectively.

3) The model can be used to contrast and compare two different alternative management actions in addition to being able to compare with the status quo. For example, in the first program run suppose the base case was a status quo season opening on December 1 with a $3.00 starting ex-vessel price. Now suppose the season was delayed by four weeks due to crab meat yields being below standards and the starting price was $2.85. The results from each set of program runs could be easily imported into an external program (e.g., another Excel spreadsheet) and subtracted from each other. Comparing the two cases would show that delaying the season one month and starting at lower prices would result in a decrease of harvest revenue of $13.6 million and a decrease in community impacts of $20.3 million.

4) Model runs demonstrated that the effects of natural mortality are magnitudes greater than the effects of handling mortality and that any savings that might be gained by soft-shell management protection would comparatively be very small. For example, the model showed that an eight-week early closure results in an increase of 231 thousand pounds in handling mortality while during the same eight-week period sublegal and legal natural mortality totaled 12.7 million pounds. These results illustrate the importance of resource scale and environmental variability. Results also illustrate the "sensitivity" of the model to various assumptions, and underscores the need for additional research in determining the accuracy of critical economic and biological variables given their significant effects on determining the "best" management actions.

Developing a Dungeness crab bioeconomic model provides a tool to inform decision making about the impacts of fishery management policies and practices. The model methods were not developed to necessarily advance bioeconomic modeling theory, but to provide a management-level tool for generating economic results. As a seasonal management model, the tool has limitations for analyzing long-term harvest effects that may extend across many seasons. The value of using the tool is to increase understanding of biological and economic interactions and to formulate changes in policy that can increase management benefits. Having economic impact information readily available can foster heightened collaborative relationships among stakeholders for managing the fishery.

Table ES.1
Season Biomass and Mortality Accounting for Base Period With an Eight-Week Early Closure Management Action

	Base Period	Difference	Results	Percent Difference
Beginning biomass			174,381,912	
Existing			34,048,579	
Recruitment			140,333,333	
Handling mortality	335,837	-230,884	104,954	-68.7%
Sublegal soft	21,500	---	0	-100.0%
Sublegal hard	109,078	-8,024	101,054	-7.4%
Legal soft	142,916	---	0	-100.0%
Legal hard	6,441	-2,542	3,899	-39.5%
Cannibalism/predation	55,902	---	0	-100.0%
Retained catch	16,696,522	-32,011	16,664,511	-0.2%
Natural mortality				
In season			92,812,661	
After season			16,298,387	
Total fishing and natural			125,880,513	
Ending biomass			38,525,609	
Discards	19,668,743	-3,055,663	16,613,080	-15.5%

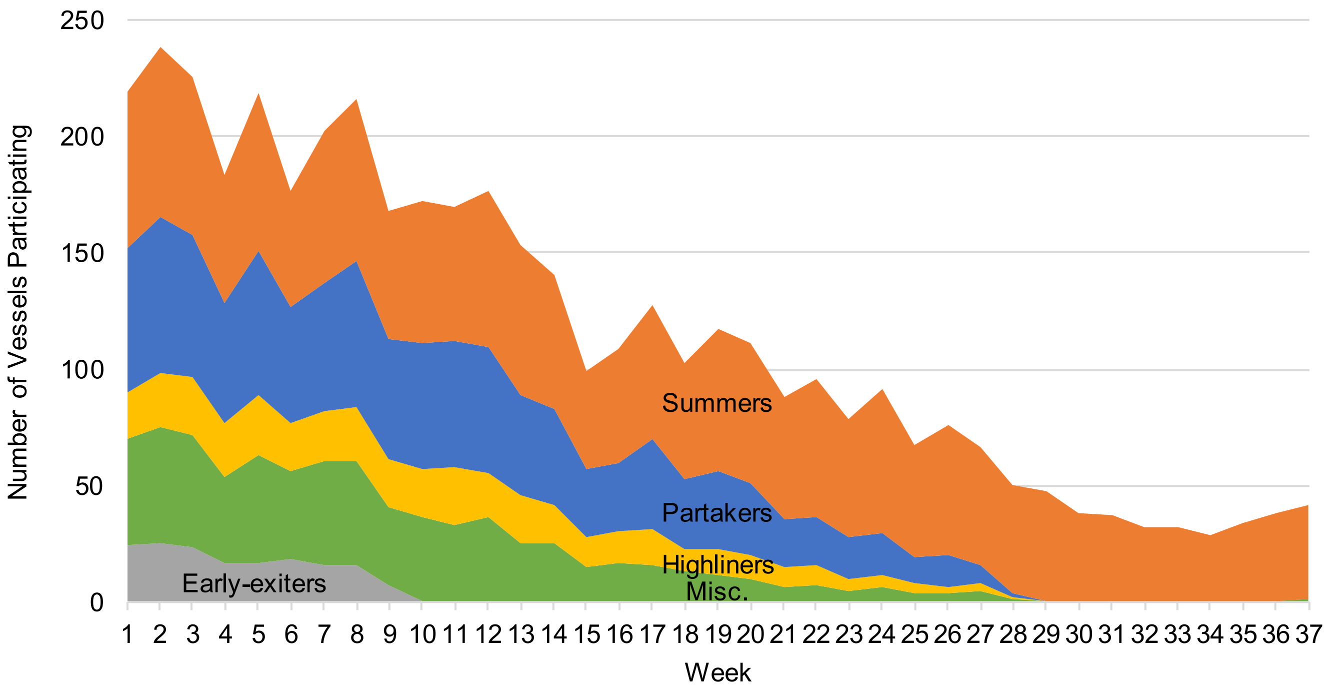
Notes:
1. Table values are pounds.
2. Difference includes current and following seasons. Biomass and natural mortality are for current season.
3. A dash in the difference column means the calculation approximates the base period amount.
4. Discards are either gender, any size, and any condition (live or dead). They are total removals minus retained catch. Handling mortality is that portion of discards that are male and sublegal/legal size. They are either dead on deck or will have a delayed death once discarded.

Table ES.2
Season Economic Impacts for an Eight-Week Early Closure Management Action

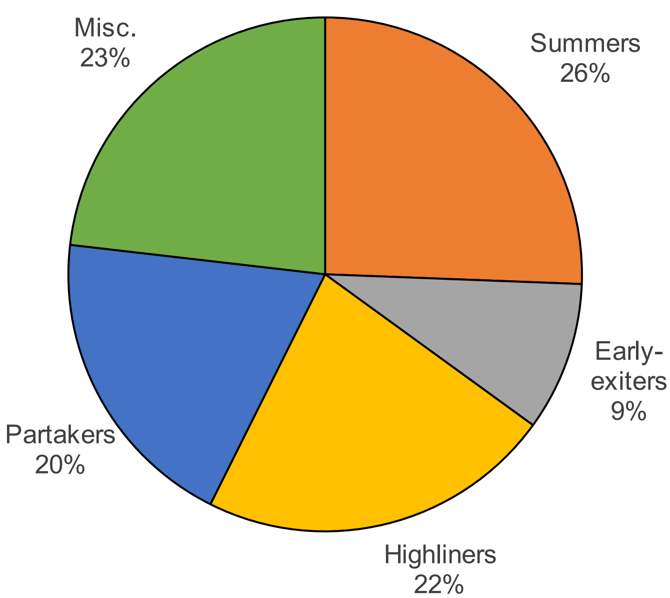
	Base Period	Difference	Results	Percent Difference
Harvester				
Pounds	16,696,522	-32,011	16,664,511	-0.2%
Revenue	43,904,894	-214,196	43,690,699	-0.5%
Profitability	22,251,421	-78,822	22,172,600	-0.4%
Processor				
Wholesale value	68,861,645	-262,044	68,599,601	-0.4%
Communities				
Income	70,705,888	-301,382	70,404,506	-0.4%
Processor	14,711,306	-28,205	14,683,100	-0.2%
Harvester	55,994,582	-273,177	55,721,405	-0.5%
Total job equivalents	1,768	-8	1,760	-0.4%

Notes:
1. Difference includes current and following seasons.
2. Total job equivalents are average full and part-time jobs based on annual average net earnings, and assuming average income per job of $40,000. Statewide and coastwide average earnings for 2013 were $45,783 and $34,137, respectively.
3. Income includes "multiplier effect" at the state level.

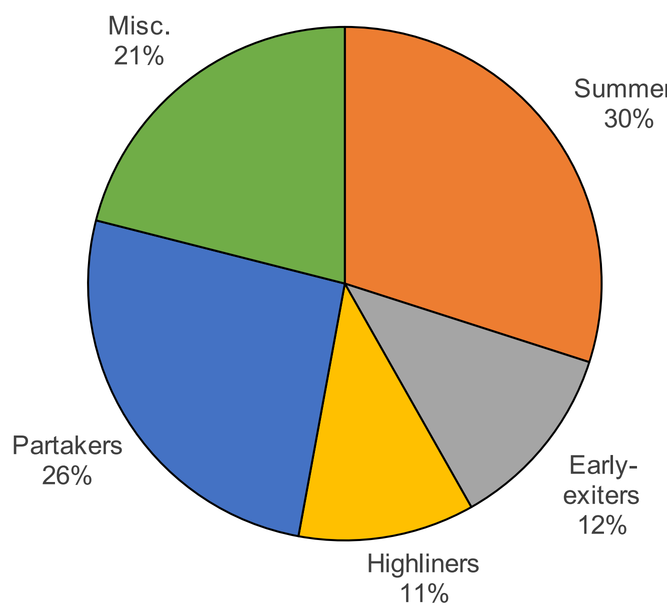
Figure ES.1
Vessel Participation by Vessel Classifications for Base Period



Shares of Oregon Ocean D. Crab Revenue (Real$)



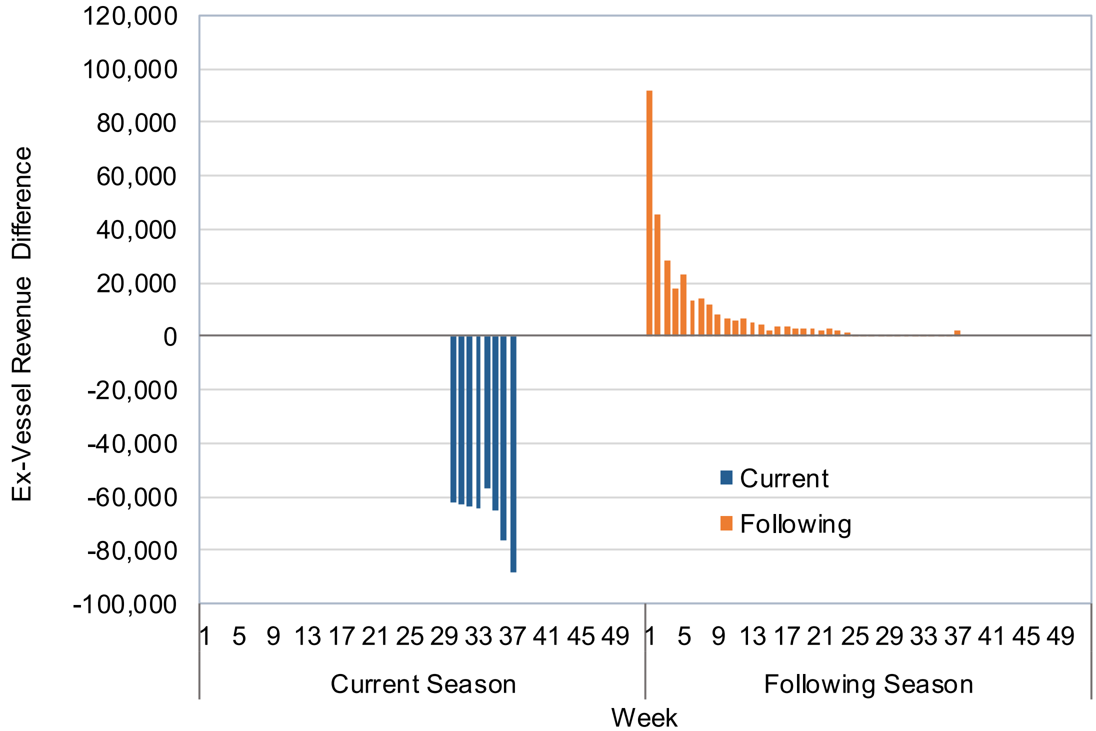
Shares of Vessels



Notes: Classification descriptions by hierarchy order are:

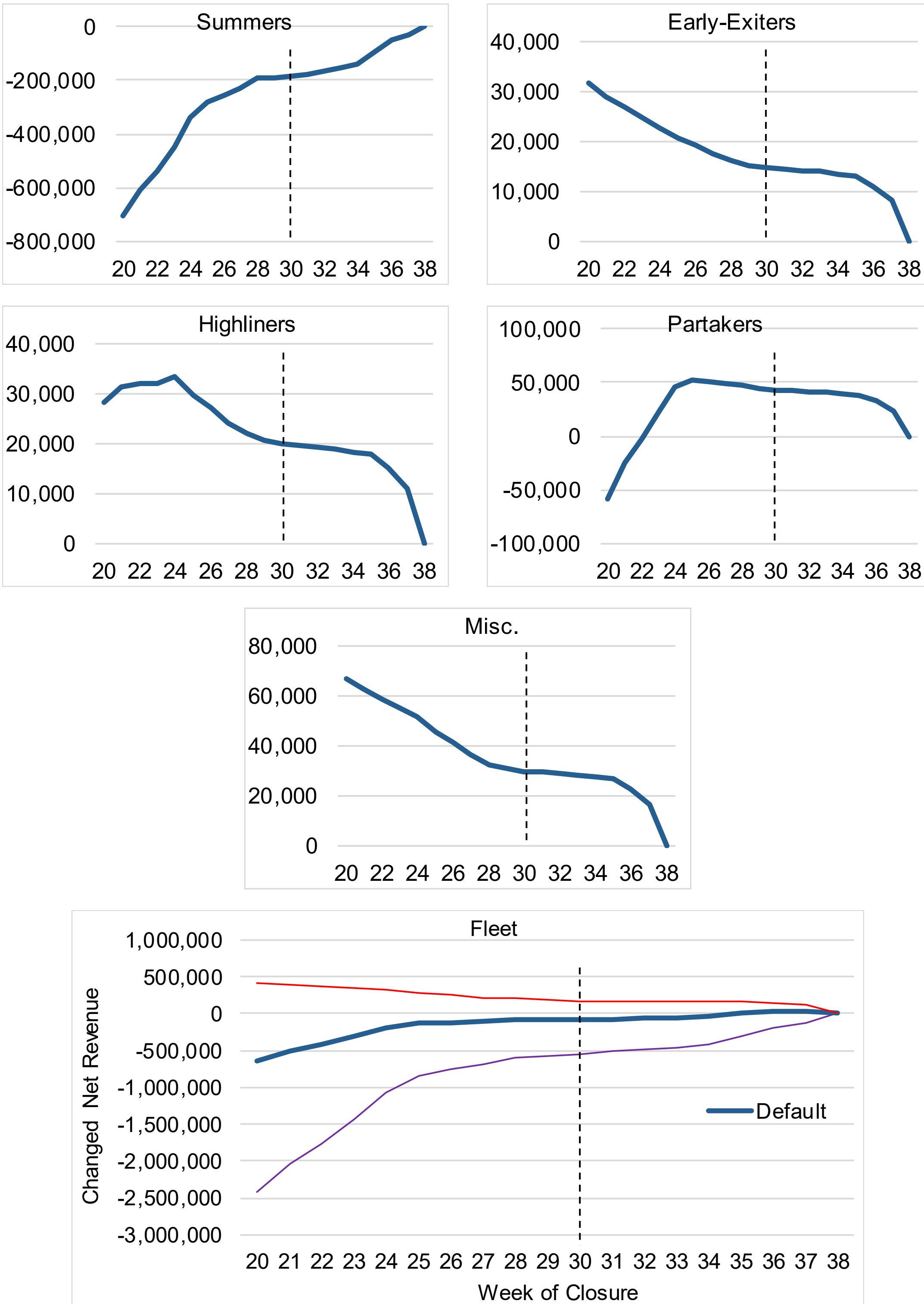
1) Summers: Vessels harvest Oregon ocean D. crab on or after June 10 and on or before August 14.
2) Early-exiters: leave fishery on or before January 31.
3) Highliners: D. crab is majority of revenue and total revenue greater than $250,000.
4) Partakers: D. crab is majority of revenue and total revenue less than or equal $250,000.
5) Miscellanies: D. crab less than a majority of revenue.

Figure ES.2
Harvest Value Weekly Difference for an Eight-Week Early Closure Management Action



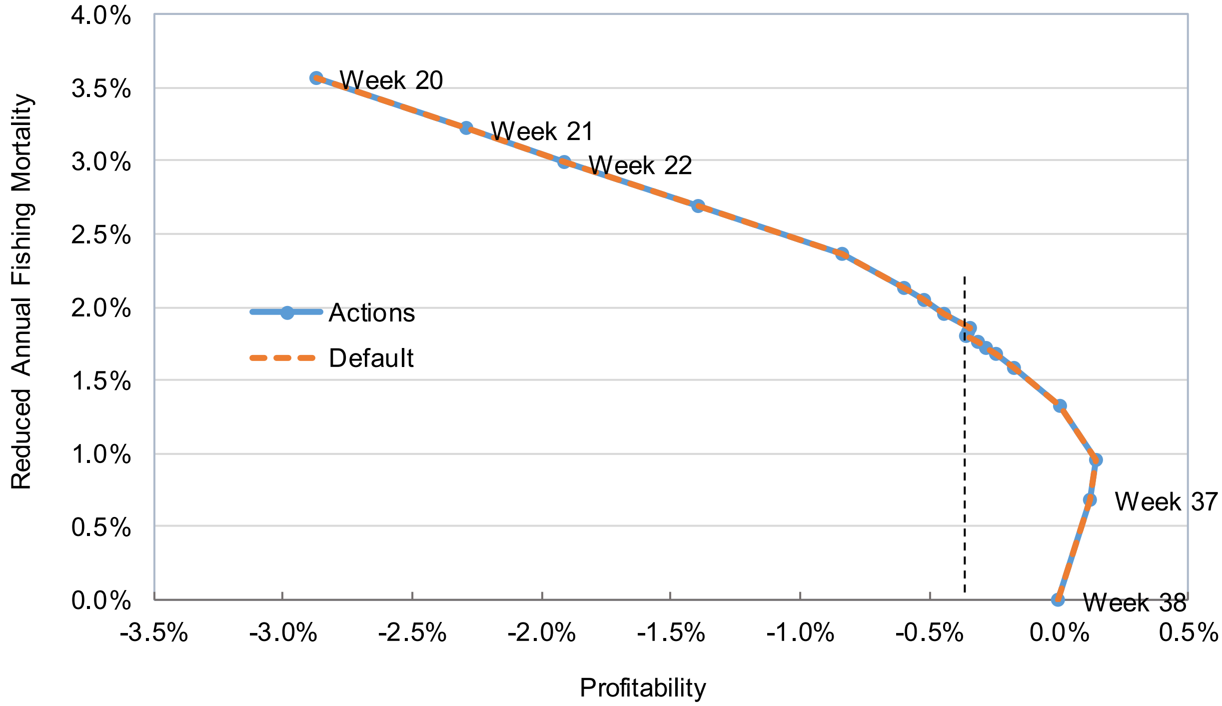
Note: Difference is based on action minus status quo.

Figure ES.3
Profitability Impacts by Vessel Classifications for Early Season Closure



Notes: 1. The dashed vertical line shows season timing for an eight-week early closure.
2. High and low are dashboard status quo settings that maximize or minimize profitability at the end of the current season.

Figure ES.4
Conservation and Profitability Tradeoff for an Eight-Week Early Closure Management Action



Notes: 1. Each dot represents an early closure week from Week 20 to 38. The dashed vertical line shows season timing for an eight-week early closure.
2. The analysis did not include modifications to model assumptions, therefore the management action alternative's trajectory is superimposed on the default assumptions trajectory.
3. The *y*-axis percents are actions minus status quo divided by status quo.
4. The base period annual average fishing mortality is 17.0 million pounds (280 thousand pounds handling, 56 thousand pounds cannibalism, and 16.7 million pounds retained catch). The base period annual average net revenue is $22.3 million.

(this page is intentionally left blank)

I. INTRODUCTION

A. Purpose

This report describes the results from developing an Oregon Dungeness crab commercial ocean fishery bioeconomic model. The project sponsor is the Oregon Dungeness Crab Commission. The Commission appointed a steering committee to oversee development of the model.

The objective for developing the bioeconomic model was to provide a tool for simulating a season under a relatively narrow set of changed fishery management actions that address conservation concerns. Other applications of the model, such as finding long-term optimal exploitation levels through quota or other management policies, will require future research and additional model development.

The project had two main deliverables. The first was to show economic analysis results for closing the ocean fishery season early to reduce incidence of soft-shell crab discard mortality. The second deliverable was to provide an easy to use computer program that would allow for the analysis of other management actions or to test changing modeling assumptions. This report describes the results for the first deliverable. The second deliverable is a computer file and user guide available from the project sponsor. The model is developed in Microsoft Excel software.

B. Background

Oregon's commercial ocean Dungeness crab fishery is usually the state's most valuable fishery. The fishery's harvest value was highest eight times out of the last 10 years ending in 2016 using a crab season and other fisheries calendar year harvests for comparison. During this study's adopted base period (seven seasons 2007-08 through 2013-14) landings averaged about one-third of all the onshore harvest value. The base period average landings were 16.7 million pounds with a harvest value of $43.9 million per season. Annual catch was variable at +/- 39 percent during the base period. The Oregon ports with the greatest engagement based on harvest value in 2014 were Newport (34.1 percent), Coos Bay (24.3 percent), and Astoria (22.6 percent). Among ports with landings greater than $1 million harvest value in 2014, the highest dependency on Dungeness crab were Winchester Bay (78.0 percent), Garibaldi (56.4 percent), and Port Orford (43.2 percent). The commercial ocean crab fishery landings are an important complementary product flow at many other smaller landing ports along the Oregon Coast. A few vessels participate in a commercial bay fishery in the fall after the ocean season is closed. There is also an active recreational crab fishery that takes place both in estuaries and the ocean. Dungeness crab is considered an iconic retail product and many Oregon Coast visitors have expectations for purchasing year around, fresh, locally caught crab as a seafood restaurant menu and store item.

The ocean crab fishery is state managed. It became a limited entry fishery starting with the 1995-96 season. There were an average 321 vessels out of a permitted 424 vessels that participated during the project's seven-year base period for seasons 2007-08 through 2013-14. Vessels fished approximately 116 thousand pots out of an authorized 150 thousand pots. There are limits on pots per vessel categorized by three tiers (200, 300, and 500) that were originally assigned to vessel permits for the 2006-07 season depending on catch history.

Resource conservation is attained by using a "3-S" management strategy for size minimum 6.25 inch carapace width, sex male, and season start and duration. The traditional season start is December 1 (if meat yield and crab quality meet standards) and ends on August 14. The existing management season ending date was selected as a compromise to allow for some summer deliveries and still protect against soft-shell crab handling mortality. There are two additional soft-shell crab protection provisions: cumulative weekly trip limit of 1,200 pounds starting the second Monday in June, and early season closure if the total summer (June through August) catch exceeds the winter and spring (December through May) catch by 10 percent. The crab moulting process that causes the soft-shell condition starts in the spring and peaks during the summer months in Oregon. Soft-shell crab is not marketable and is discarded.

A result of gaining Marine Stewardship Council certification for the Oregon fishery in 2010 (which was allowed to expire in 2015) was to adopt a generational harvest control rule reference point. A four-year decreasing inter-season landing trend coupled to threshold landing and CPUE levels triggers development of additional conservation adaptive management actions.

Despite the fishery's economic importance, there are many gaps in our scientific understanding that limit our ability to model economic impacts. This clashes with managers and industry interest in knowing the impacts from management changes, such as closing the season early to avoid the peak moult period mortalities.

C. Methods

A deterministic bioeconomic model was developed to simulate the fishery. The model has biological and economic inter-relationships which allows, for example, the ability to determine how changes in assumptions about crab resource growth and recruitment will affect harvester and processor profit. In turn, changes in the fishery including harvest management practices may decrease/increase future year resource abundance. To support use of the model, graphs and tables of fishery trends and characteristics that were used to develop the model are provided.

The Dungeness crab biomass used in the model is mature male sublegal and legal size cohorts. The sublegal portion of biomass includes the pre-recruitment crabs that will contribute to the fishery biomass in the next season. A conserved portion of the biomass that is from changed management, such as early closure, is defined to be "carryover biomass." It includes avoided catch and handling mortality. The carryover biomass is subject to natural mortality and a post-moult growth rate is applied.

A model user can change inputs and concurrently view results from those changes. The effects from changing model assumptions and management options are for a current season and one following season. The carryover biomass is not tracked in additional seasons because it is very small due to high natural and fishing mortality during the one following season.

The model uses a vessel five sector classification scheme in order to improve model accuracy and understand how changes in policies impact different sectors of the fleet. The information can be used to compare and contrast how results affect fleet sectors differently.

Although the model was designed primarily to evaluate the effects of early season closures, it accommodates three major types of policy options:

- Altering effort. Vessel counts can be changed over a range of +/- 10 percent. The resulting change in effort is predicted using several participant behavior variables. Catch is calculated from the effort prediction using a time variant catchability coefficient.
- Delaying season opening. The season can be delayed up to seven calendar weeks. Effort predictor variables such as revenue-per-unit-effort and catchability presume a traditional December 1 start for whenever the model user inputs a season start. Price trends also assume a traditional season beginning and duration pattern.
- Closing the season early. The season can be closed as early as Week 21 (about April 15) which corresponds to a relatively low probability that adult crab are in a moult condition.

Many assumptions had to be made in the model development, and user controls conveniently available on dashboards, allow testing the sensitivity in results from modifying the assumptions. Controls are operational for both current and following season calculations, except as noted on the dashboards. Real-time calculations of the effects are shown on graphs and tables adjacent to the user controls.

Results from changing model assumptions and investigating management options are the differences between a simulated status quo season and a new fishery situation arising from user controls. The new fishery total economic measurements are calculated by adding the difference to the base period economic measurements. (The difference between the status quo case and the alternative case could be negative in which case the difference is subtracted from the base period.) The metrics include: pounds, harvest value (ex-vessel revenue), harvester profitability (ex-vessel revenue minus trip variable costs), wholesale value, processor value added, community economic impacts, and handling mortality. The community economic impacts are measured by changes to household income and job equivalents. The impacts include economic "multiplier" effects.

Model outputs are intra-season (weekly) and are summed for a whole season. Tradeoff curves are provided for profitability versus indexes for conservation, equity, community economic impacts, and compensatory harvester revenue opportunities.

D. Report Contents

The report contents are comprehensive and support the use of the model as a learning tool. The tool is in the form of a user friendly, interactive computer program that allows learning and discovering about the fishery and its management.

The first seven chapters (Chapters II-VIII) of the report cover descriptions about fishery data and sources, fishery management, life cycle stages, fishing and natural mortality, harvest effort and trip measurements, vessel classifications and trip costs, and seafood product yields and processing costs. The next chapter (Chapter IX) describes the crab resource and fishery existing conditions. Displays showing base period trends and patterns provide the user an understanding of fishery activities and economics that occurred during the period. Reviewing the displays should assist the user in developing new management scenarios that reflect possible future conditions and management policies. Chapter X contains descriptions about modeling method biological and economic relationships and default assumptions. This chapter is supported by an appendix with content for model development statistics and assumption sensitivity analysis. Chapter XI provides results and interpretations for a range of management specifications. While the model is complete for satisfying project objectives, there are many enhancements and added capabilities that could improve the model. Chapter XII suggests other research and other useful features that might be included in future model development. The final Chapter XIII contains summary result discussions.

II. FISHERY ACTIVITY DATA SOURCES

Seven seasons of fishery activity data (2007-08 through 2013-14) for ocean catch-area harvesting were used for the analysis base period. Effort, landing data, and vessel information is derived from logbooks, fish tickets, and permit registrations.

The base period was chosen because of the availability of logbook data. It is fortuitous that the period encompasses a broad range of annual harvest volume and prices. Reasonable results should be expected when testing model assumption modifications and developing management scenarios that are within the range of data used to establish the model relationships.

Logbook submittals are mandatory for the Dungeness crab fishery starting with the 2007-08 season. ODFW entered all submitted logbooks in a database the first four years of the program. ODFW in recent years only enters a one-third random sample of logbook submittals. The sample data is expanded for the analysis to represent fleetwide effort using the sample rate and compliance factors (Table II.1).

Landing information is derived from fish tickets issued by the first-buyer for the harvest purchase. Or in the case of a harvester selling to the public, the harvester submits direct sales reports. Delivery counts are not corrected for multiple fish tickets being issued for one harvesting event. Landings exclude research and discard disposition, and Dungeness crab bay fishery harvests. Permit registration data provided tier endorsement, vessel size, and other information for each participant.

Data is reduced to a weekly time resolution. The August 14 closure date corresponds to Week 37 for traditional season December 1 opening date. Some analysis relied on all catch dates being adjusted as if the first week is associated with a December 1 opening. The adjustment is necessary to generate a consistent time alignment when averaging over seasons that had different opening dates. For seasons when the opening calendar week is adjusted to Week 1, the effective closure date would be an earlier season week.

Table II.1
Logbook Sampling and Compliance

Season	Compliance Rate	Sampling Rate
2007-08	68%	100%
2008-09	78%	100%
2009-10	90%	100%
2010-11	92%	100%
2011-12	94%	30%
2012-13	93%	30%
2013-14	95%	30%

Note: 1. Compliance rate is logbook share of fish tickets compared to fish tickets. Sampling rate is the number of logbook submittals entered into the database by ODFW.

(this page is intentionally left blank)

III. FISHERY MANAGEMENT

The three West Coast states manage the Dungeness crab fishery individually. Management would typically be assumed by the Pacific Fishery Management Council under the Magnuson-Stevens Act since it is a fishery that takes place both outside and inside state territorial waters. Congressional legislation has allowed for state management within the EEZ since 1996.[1] The Oregon fishery's limited entry program started with the 1995-96 season and the pot limit program started with the 2006-07 season. Seasons are not managed with a pre-season quota. Each West Coast state manages the fishery under the "3-S" strategy. In Oregon, the strategy is for size (minimum carapace width 6.25 inches), sex (male only), and season (open on December 1 and close on August 14). There are other management regulations on pot design, pot markings, pot deployment, and pot minimum retrieval times (OAR 635-005-0225 through 0565). Season opening dates are dependent on crab meat density and quality standards.[2] The closing date is set by Oregon administrative rules without regard to resource soft-shell crab conditions. There is a provision to close the fishery early if the June through August catch exceeds 10 percent of the December through May catch.[3] There is

> History and Purpose of 3-S Management Strategy
> ODFW (1999)
>
> "The strategy insures high levels of annual reproduction, protects all females from harvest and adult males below the commercial minimum size of 6.25 inches. Season regulations are designed to ensure that the harvest occurs well after molting, allowing a period of time to protect newly-molted soft-shell crabs … while they harden-up and reach an acceptable meat content. The traditional approach of West Coast harvest strategies [was] to close the season during the period when the majority of adult male crabs are soft-shelled, in order to optimize the annual yield from the crab resource. However, both Oregon and Washington seasons currently extend into a period when molting activity and soft-shell abundance is typically high (July and August). The setting of season regulations has been an active issue since the early days of the crab fishery. As early as 1911, there were regulations which recognized the months of July, August and September as the times when crabs were in the poorest condition. In 1948, season closure and opening criteria were established on the basis of at-sea sampling. When more than 10 percent soft-shells were present, the season was closed. Since then, fixed season dates have been established, modified and extended. In 1984, following several years of high-volume fishing on low quality crabs at the end of the season, ODFW Commission set the season closure date to the current August 14. Late-season … landings and effort declined for several years but soon began to increase. In 1992, the Commission enacted a summer harvest quota, requiring the [ODFW] Director to close the season if landings after May 31 exceed ten percent of the previous December through May total landings. In 1999, the Commission enacted additional summer fishery regulations to discourage the potential for expansion of a soft-shell fishery, higher levels of fishing effort and increased sorting and associated mortality. Regulations restrict landings to 1,200 cumulative pounds per vessel per week during the period of the second Monday in June to August 14 … This action preserved a modest historic low volume summer fishery directed towards available hard-shell crab and coastal consumer markets."

---

1. Congress is considering the extension of the state management authority permanently with a West Coast Dungeness Crab Management Act (Senate Bill 1143 and House Resolution 2168). The current authority expired September 30, 2016.
2. The season opening for the commercial ocean Dungeness crab fishery may be delayed in one or more fishing zones based on the results of crab meat yield and quality testing. The pre-season testing protocol for the Pacific States Marine Fisheries Commission Tri-State Coastal Dungeness Crab Program specifies the process for establishing fishing zones and coordinating the opening of the fishery in Washington, Oregon, and California north of Point Arena. The Tri-State Dungeness Crab Program exists as an interstate cooperative agreement. The agreement promotes state management consultation.
3. The restriction on the cumulative share of summer landings has been revised in the last 25 years (ODFW 2016). The 10 percent summer harvest cap was put in place starting with the 1992-93 season. It was reduced to seven

also a 1,200 pound weekly landing trip limit starting the second Monday in June. The actual opening dates for the ocean seasons within the base period are shown in Table III.1.

There is a commercial bay fishery which occurs from the day after Labor Day to December 31, except on holidays and weekends or during December when the ocean fishery is closed. Any ocean permitted vessel can participate in the bay fishery. The operating gear must be 15 or less crab rings.

There are an average 321 vessels out of a permitted 424 vessels that participated during the base period. They fished approximately 116 thousand pots out of an authorized 150 thousand pots. There are limits on pots per vessel categorized by three tiers (200, 300, and 500). The limits were originally assigned using documented catch statistics during a historical period. The limits from a permitted vessel not being fished cannot be stacked on another permitted vessel. Permits can be transferred to another vessel once during an 18-month period under certain constraints such as the recipient vessel cannot be more than 10 feet longer and cannot exceed 99 feet length.

There are no set resource soft-shell condition or abundance reference points that trigger additional harvest control rules for the fishery. Heppell and Thompson (2010) did recommend a placeholder reference point for the fishery that could be used until scientific stock assessments are made. The ODFW subsequently adopted a reference point definition and outlined adaptive management responses that could take place (ODFW 2014). The reference point is:

> Landings have declined for three consecutive seasons and are projected to decline for a fourth consecutive season (based on early season landings in the fourth season) to fall below 20 percent of the 20 year average; and logbook CPUE falls below the average level predicted to have occurred over the 1980-81 through 1986-87 seasons.

An adaptive management response could include season closure, reduced pot limits, trip limits, area closure, and increased minimum size limit.

According to Heppell and Thompson (2010), the reference point would never have been reached in the Oregon or Washington fishery. It would have been reached once in the California fishery in 1964.

Table III.1
Season Opening Dates

Season	Earliest Season Opening Date	Description
2007-08	12/1/2007	Dec. 1 coastwide
2008-09	12/1/2008	Dec. 1 coastwide
2009-10	12/1/2009	Dec. 1 coastwide
2010-11	12/1/2010	Dec. 1 coastwide
2011-12	12/15/2011	Dec. 15 north of Gold Beach /Jan. 15 south of Gold Beach
2012-13	12/31/2012	Dec. 31 north of OR/CA border/ Jan. 15 south of OR/CA border
2013-14	12/16/2013	Dec. 1 south of OR/CA border/ Dec. 16 north of OR/CA border

---

percent at the same time the 1,200 pound weekly trip limit was implemented beginning in the 1998-99 season. It was then increased back to 10 percent in the 2002-03 season and has remained at that cap since then.

IV. LIFE CYCLE

Dungeness crab (*Cancer magister)* are members of the highly evolved brachyuran (true crab) infraorder of the subphylum Crustacea. They are commercially significant and widely distributed in coastal waters of the eastern Pacific Ocean from Santa Barbara, California, to the Pribilof Islands (Jensen 1995). Research conducted over the species' range has shed light on the biology, physiology, and ecology of Dungeness crab, and has provided insight into how the commercial and recreational fisheries may affect the population (Jensen and Armstrong 1987). However, there remains a deficit of information in the literature specific to Oregon, as well as all areas occupied by Dungeness crab, regarding the timing of the moult, intra- and inter-annual migration, harvest rate, time variant catchability, spawning stock biomass, annual recruitment, and composition of the population with respect to sex ratios and size frequencies.

Some pertinent research findings are:

- Adult Dungeness crab live in coastal regions, including continental shelf, small estuaries, and inland waters; depth range from intertidal to approximately 230 m (Jensen 1995).
- There is a common belief that crab move to deeper water in winter and inshore in the summer. Yochum et al. (2017) found that crab are most abundant in shallow water in the late spring and summer, but also abundant there in December. Sampling and tag returns reflects the location of harvest which in turn reflects not only abundance but weather and ocean conditions. Diamond and Hankin (2011) found large numbers of distributed tagged crabs recovered in shallow sandy areas during spring months, but ruled out statistical significance because of fishing ground choice. They did conclude adult female Dungeness crabs appear to constitute extremely localized stocks in northern California. In regards to latitudinal migration, Cleaver (1949) and Jacobson (2011) state that crab tagged in early winter months tended to move northward with the approach of summer.
- Males and females are mature at three years (Cleaver 1949). Males mature by 5.4 inches (MacKay 1942). Males reproduce for one or two seasons before recruiting into the fishery (Didier 2002) at 6.25 inches for the Oregon commercial fishery. Some crab are 6.25 inch by three years, but majority not until the latter half of their fourth year (Cleaver 1949).
- Timing of the moult varies geographically (south to north in timing), annually, and by sex (Robinson et al. 1977, Demory 1985, Dunham et al. 2011). In Oregon, moulting occurs from March to September (Rasmuson 2013). Females moult earlier in spring and males later in the summer. It appears that the period of peak moulting activity is usually from mid-May through mid-August south of Cascade Head, and from July through September north of Cascade Head. During and immediately after these peak periods, most of the stock of crabs slated for the next season's harvest are of legal size but are soft-shelled (ODFW 2014). Each newly-moulted recruit requires a minimum of eight to twelve weeks to approach the level of meat content (23 percent north of Cascade Head, Oregon and 25 percent south of Cascade Head, Oregon) chosen as minimally acceptable in the winter fishery (Dunham et al. 2011, Rasmuson 2013).

- Female crab exhibit assortative mating behavior. Females require mates that are larger than their size (Butler 1960, Shirley and Sturdevant 1988).
- Female fecundity increases with carapace width, range, and previous moulting history. Higher fecundities are found for crab that had moulted during the most recent season with up to a maximum of about 2.5 million with a typical range of 0.1 to 1.6 million. The high potential fecundity of large females is tempered by a decrease in moult frequency with size, which results in a reduction in relative fecundity (Hankin et al. 1985, 1989).
- Natural mortality is from disease, competition, density-dependence reproduction, senescence, and predation on eggs, larvae, post-larvae crab (cannibalism, etc.). Zhang et al. (2004) suggests an instantaneous natural mortality rate of 1.25 per year for adult moulting and non-moulting periods. Tegelberg (1972) suggests a 6.8 percent factor for cannibalism/predation on soft-shell crab in pots. Windsland (2014) discusses the comparison of natural mortality of Dungeness crab with other crab species.
- Lifespan is 8-10 years (Gutermuth 1989).
- Once 10 cm carapace width is reached, size will only increase nine and 15 percent for males and females, respectively (MacKay 1942). After reaching a size of 10 cm in females and 15 cm in males, moult increments begin to decrease. Finally, at about 16 cm in females and 19 cm in males, moults are virtually absent (Wainwright and Armstrong (1993).
- Estimated exploitation rates along Pacific coast range from 0.51-0.92 (Gotshall 1978, Jow 1965, Methot Jr. and Botsford 1982, Smith and Jamieson 1989); and, change annually by area (Methot Jr. and Botsford 1982) and with abundance (Jow 1963). Smith and Jamieson (1989) speculated that a large fraction of females may go unmated in many fisheries since females exhibit assortative behavior. Despite selective harvest of large males, Oh and Hankin (2004) and Rasmuson (2013) suggest the fishery does not seem to impact mating success.
- There is increasing research results becoming available about environmental variables driving fluctuations in stock abundance. Hobbs et al. (1992) suggested the survival of crab larvae is unpredictable and is independent of inter-annual variation in the environment, and megalopae abundance is not correlated with salinity, temperature, dissolved oxygen, or chlorophyll levels. However, Shanks and Roegner (2007) has shown larvae counts are correlated with the California Current spring transition (seasonal shift in atmospheric forces the drive ocean currents), and further, megalopae counts can be related to four-year later adult stock abundance (measured by catch). Miller et al. (2016) found that ocean acidification could have a measurable deleterious impact on Dungeness crab population dynamics. Byrne and Przeslawski (2013) synthesizes literature about ocean warming and acidification effects on invertebrates.
- Annual fishery recruitment and, therefore, annual landings appear to be influenced predominantly by environmental forcing rather than fishing (Hankin et al. 1985, Heppell and Thompson 2010). Washington, Oregon, and California ocean catch data indicates a cyclic pattern in landings with a periodicity of 9-10 years. This cycle is attributed to environmental and density-dependent influences, the exact mechanism of which is incompletely understood (Johnson et al. 1986, Higgins et al. 1997).

The modeled biomass is mature male adults of sublegal and legal size. The reason for choosing this selected gender and size is current management regulations are for a minimum size and obligate discard of females. Male crab in Oregon and Washington are mature at approximately three years old and recruit into the fishery at approximately age four (MacKay 1942, Cleaver 1949). The minimum size means males have been reproducing for one or two seasons. This maintains high levels of eggs-per-recruit and the reproductive potential of females is protected (Heppell and Thompson 2010). Female fecundity is not a significant driver in inter-annual recruitment variation into the fishery. Given the number of unknowns in the literature and inter-annual variability in biomass and pre-recruit mortality, it is preferable to introduce crab to the model as age three pre-recruits.

(this page is intentionally left blank)

V. FISHING AND NATURAL MORTALITY

Fishing mortality used in the model has three components: handling mortality, cannibalism/predation in pots, and retained catch. For handling mortality, Yochum et al. (2017) estimated discard kills per retained catch for four crab cohorts (legal soft, legal hard, sublegal soft, and sublegal hard) based on "ride-along" sample data.[1] Handling mortality rates included deck observed (immediate) and delayed discard kills. Smoothing curves were fit to the Yochum et al. (2017) data for use in the bioeconomic model (Appendix C). ODFW ride-along and dockside monitoring data supplemented the Yochum et al. (2017) reported data and helped direct model development.[2] A 6.8 percent factor for cannibalism/predation in pots was from Tegelberg (1972) to be applied to the presence of soft crab in pots. The presence of soft-shell crab present in the pot prior to pulling is about five times the soft-shell handling mortality per retained catch ratio as estimated by Yochum et al. (2017). Retained catch was estimated from fish ticket data for the base year historical period.

The natural mortality rate was derived from Zhang et al. (2004) who suggested a representative adult natural mortality instantaneous rate of 1.25 per year averaged for moulting and non-moulting periods. This translated into a natural mortality weekly biomass depletion factor of 2.4 percent.

A post-moult growth rate was applied to the carryover biomass, i.e. the avoided catch and handling mortality that comes from specifying a management action. MacKay (1942) found that males up to 15 cm carapace width grow at about nine percent per moult. A 10 percent rate was assumed for the default.

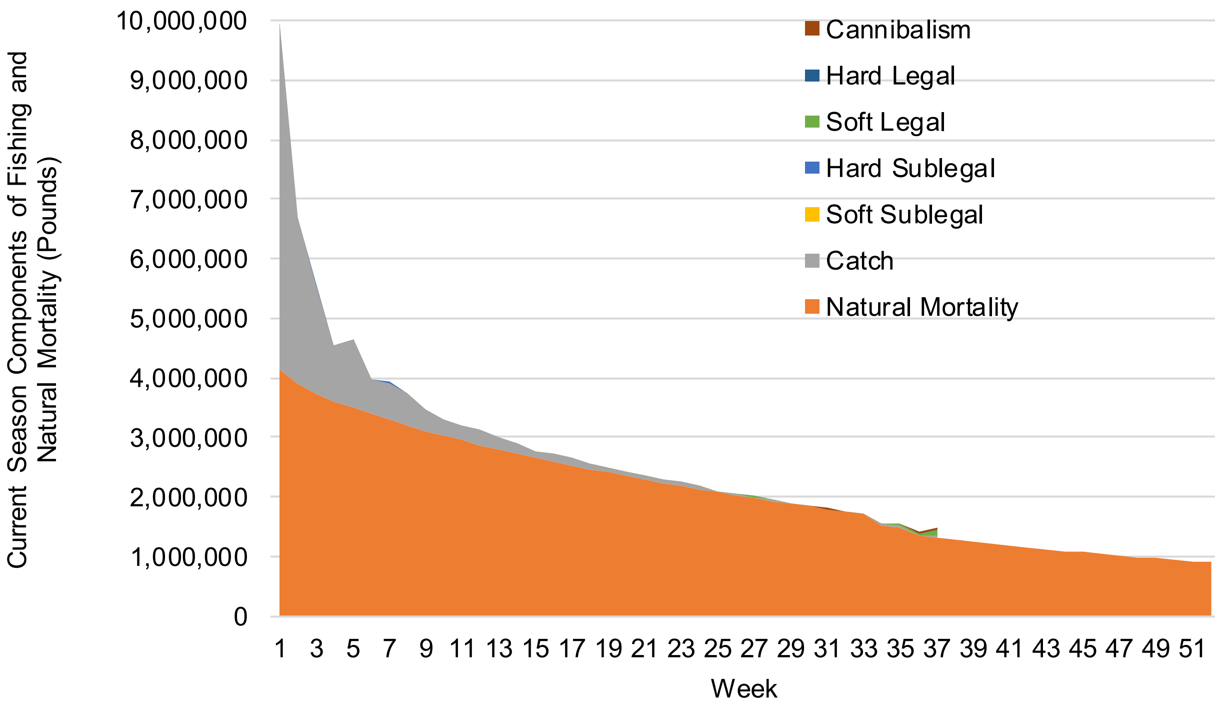
Figure V.1 shows the base period weekly calculated natural and fishing mortalities. There are additional Dungeness crab mortalities not shown in the figure including mortalities from incidental catch in other commercial fisheries and the Dungeness crab recreational fishery. Somers et al. (2014) reported on total discard mortality in the 2013 West Coast fisheries: 0.05 mt for the whiting at-sea and shoreside fisheries; 150.87 mt in the Limited Entry trawl and fixed gear fisheries; 6.7 mt in the Open Access fixed gear fishery; and 0.04 mt in the pink shrimp fishery. The California halibut fishery discard mortalities totaled 181.90 mt. The ratio of West Coast Dungeness crab discard mortality to total Dungeness crab mortality for "other" West Coast fisheries landings can be used to estimate crab discard mortality in "other" Oregon fisheries. These estimates include: 191 thousand pounds Limited Entry trawl and fixed gear; five thousand pounds Open Access fixed gear; and minor amounts in the whiting shoreside and pink shrimp fisheries. Oregon's recreational ocean crab fishery catch is estimated to be between 250,000 and 300,000 pounds per year for the 2009 through 2011 seasons (Ainsworth et al. 2012).

---

1. Immediate and delayed discard mortality rates (five days after release) estimated to be 0.080 (95 percent confidence interval 0.061- 0.100) for females; 0.012 (95 percent confidence interval 0.002-0.022) for hard-shell males; and 0.092 (95 percent confidence interval 0.026-0.157) for soft-shell males (Yochum et al. 2017).
2. ODFW ride-along data was used to design sampling plans and observer collection protocols in the Yochum et al. (2017) study. ODFW ride-along data results was used in an informal comparison of Yochum et al. (2017) synthesized results. The ODFW dockside data was reviewed for the possibility of developing age-growth reproduction models. Deference to Heppell and Thompson (2011) findings for adequacy directed an approach based on a one-gender (male) and two-age cohort (sublegal and legal size) virtual population analysis method.

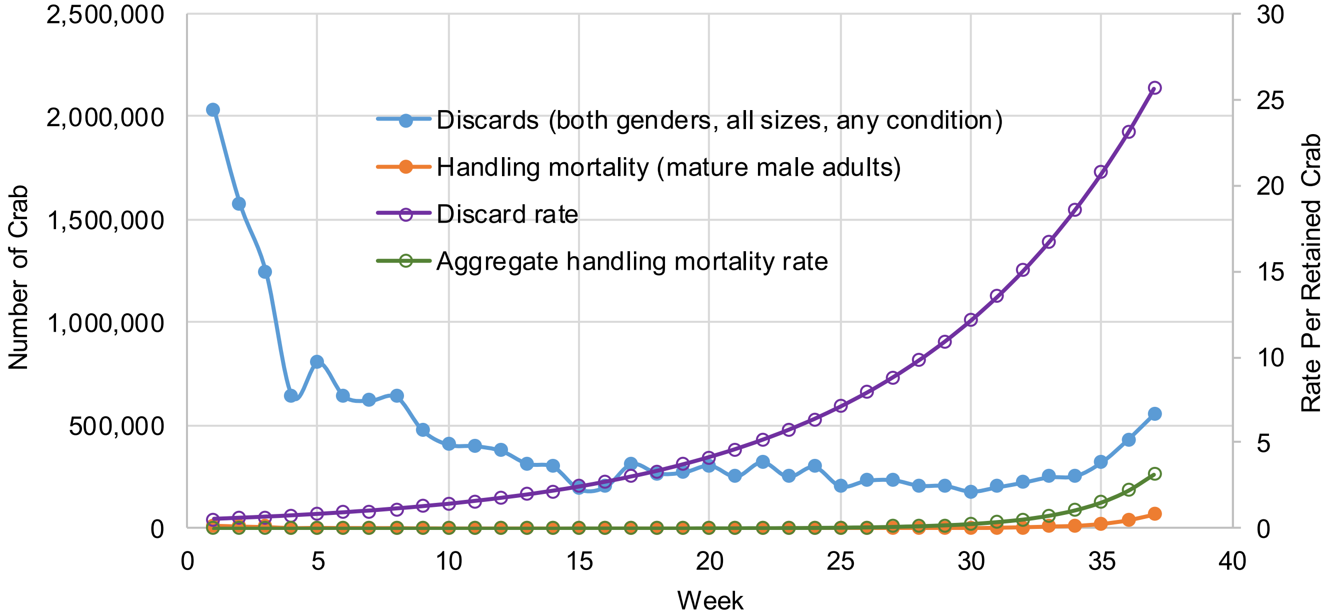
Figure V.2 shows weekly total discards (both male and female, alive and dead) and discard rates per retained crab. Discards can be substantial in summer months. For example, in Week 30 the calculated number of discarded crab per retained crab is 12 to 1. For the portion of discards that result in dead mature male crab (excludes pot cannibalism), the Week 30 proportion is 0.2 to 1.

Figure V.1
Fishing and Natural Mortality Estimates



Note: 1. Male biomass includes sublegal and legal size male crab. It is assumed all recruitment occurs in Week 1.

Figure V.2
Discard and Handling Mortality Rates for the Base Period



Source: Discard and handling mortality rate data derived from Yochum et al. (2017) and adapted for this study by using fitted curves to predict rates for each week.

(this page is intentionally left blank)

VI. EFFORT AND TRIP MEASUREMENTS

Effort may be defined as a composite measure of operational inputs that occur in a unit of time (Pascoe et al. 2004). The effort measure is useful for tracking fishery industry performance and productivity. When combined with catch, it can provide a measure of relative success and in some conditions, a measure of relative abundance through the ratio measurement of catch per unit effort (CPUE). For example, an effort measure in the groundfish fishery could be defined as net tow-hours per trip. For the Dungeness crab bioeconomic model, effort was defined as pot-pulls per trip. Logbook data provided counts of pot-pulls for the trip date. The dates were concatenated into weeks and each participating vessel was tagged according to the vessel classification scheme. This allowed for determining the weekly effort by vessel class.

Trips were defined to be a vessel harvesting event typified by a vessel leaving port with empty holds, transiting to fishing grounds, deploying and/or pulling pots, and returning to port with retained catch. A single trip may be multiple calendar days. The source for trip numbers was logbooks which provided counts for unique vessel days. Fish ticket data provided counts for deliveries. It was assumed that on a weekly basis, the two counts should reconcile and the difference would be explained by multiple day trips.[1] A smoothing curve was fit to the weekly ratio of unique vessel days and delivery counts to account for the multiple day trips. The ratio average was 1.36 in the first two weeks for the base period and decayed to 1.00 in the last two weeks of the base period. Discerning effort and trip measurements was important in the calculation of costs. Some costs were associated with effort (such as bait costs) and others with trips (such as fuel costs).

1. The fish ticket count was not adjusted for the rare occurrence when multiple fish tickets are issued for one harvesting event.

(this page is intentionally left blank)

VII. VESSEL CLASSIFICATIONS AND TRIP COSTS

Using vessel classifications for fishing fleets that have heterogeneous properties can improve the accuracy of modeling estimates. Using classifications has the advantage of helping model users identify with model results. Having the classification information also assists the analyst make appropriate inferences with respect to technical and social-economic results due to changes in management and regulation (Ferraris 2002).

For the bioeconomic model, statistical procedures were used to develop a classification scheme. The procedure generated rudimentary groupings that were manually modified to make the classification rules more transparent and understandable. The classification names, definitions, and hierarchy are:

1) **Summers.** Vessels harvest Oregon ocean Dungeness crab from June 10 through August 14.
2) **Early-exiters.** Vessels leave fishery on or before January 31.
3) **Highliners.** Vessel's Dungeness crab fishery revenue is majority of revenue and total revenue greater than $250,000.
4) **Partakers.** Vessel's Dungeness crab fishery revenue is majority of revenue and total revenue is less than or equal $250,000.
5) **Miscellanies.** Vessel's Dungeness crab fishery revenue is less than a majority of revenue.

Vessels were classified for each of the base period years, i.e. it was possible a vessel was classified differently in one year than another year. Annual revenue from fisheries other than the Dungeness crab fishery was calculated for the calendar year following the Dungeness crab fishery opening date. A vessel was included in the Dungeness crab ocean fishery during a base period year as long as one landing was made using crab pot gear. The numbers of vessels in each classification are shown in Table VII.1.

The statistical procedure was discriminate analysis. The procedure used criteria based on three objectives: habit, performance, and opportunities. The database included many vessel characteristics used to define the objectives including season tenure (habit), catch and effort (performance), and non-Dungeness crab fisheries revenue (opportunities). Other characteristics were available to show fleet heterogeneity, including vessel physical size, pot permit endorsements, and home-port (majority of Dungeness crab revenue).

The procedure was applied annually for the base historical period which allowed vessels to be in different classifications across years (fidelity to a group was not analyzed). Following the statistical procedure, five strategic groups were identified and separation rules refined. The uniqueness and exclusivity of the classification types is shown in Table VII.2.

Trip costs were needed to determine a profitability measurement. Project resources did not provide for a scientific cost-earnings participant survey. Costs were estimated based on other studies and discussions with key informants.[1] The other studies reviewed included TRG (2015),

1. After annual variable costs are assigned to the Dungeness crab fishery, the costs per pot-pull and costs per trip can be determined by using an average effort and trip count. However, the spread of annual costs across

Yonis (2010), Dewees et al. (2004), Chudnow (2012), and NWFSC (2016). The financial information was itemized for variable and fixed costs, and the tabulations were across all fisheries. Disaggregating costs associated only for the Dungeness crab fishery was estimated using a fishery revenue ratio. One issue with using some of the studies was that the financial information was annual rather than based on a trip basis. The Dewees et al. (2004) study did have trip costs, but these costs were derived from the California Dungeness crab fishery prior to pot limit management.

TRG (2015) was used as the basis for determining trip variable costs. The costs were based on annual Fishery Economic Assessment Model (FEAM) crabber vessel classification activity in 2010 and updated using key informant interviews. Provisioning costs were deducted from crew/captain shares. Variable costs for bait are associated with effort (i.e. pot-pulls). Ten interview sessions with harvester participants and discussions at steering committee meetings were used to refine costs for trips and vessel classes. Table VII.3 shows the assumed trip cost profiles for each of the five vessel stratifications.

The profitability measure is net revenue which is defined as revenues minus variable costs.[2] Economic theory suggests that net revenue at the firm level for a trip (i.e. what is termed marginal net revenue) would have to be at least zero (or greater than zero if "opportunity costs" are a consideration) for a trip to occur. Vessel owners who have vertically integrated business operations would include motives associated with processor or retail/food service operations in making fishing decisions; for example, vessel owners who need supplies of fresh crabs for their local retail business operations during tourist season summer markets. Figure VII.1 shows the base period weekly marginal revenues (summed revenue divided by summed pot-pulls) and marginal costs (summed variable costs divided by summed pot-pulls) for participating vessels.

Table VII.1
Vessel Counts by Classification

Season	Summers	Early-exiters	Highliners	Partakers	Misc.	Total
2007-08	99	46	17	89	62	313
2008-09	92	70	21	48	79	310
2009-10	98	38	37	109	44	326
2010-11	114	35	34	85	75	343
2011-12	99	19	32	115	54	319
2012-13	91	17	53	54	103	318
2013-14	79	41	55	85	55	315
Average	96	38	36	84	67	321

fisheries masks the variability that any one fishery may have on a cost category. In an example for a vessel that participates in the Dungeness crab and salmon troll fisheries, the annual variable costs for bait may be wholly due to the crab fishery yet spreading this particular cost using a fishery revenue ratio would only partially account for the actual bait costs.

2. Omitting fishery fixed costs from the analysis reduces model sensitivity to participant economic behavior. For example, vessels with late exiting from the fishery may have lower fixed costs than the vessels that exit early in the season. Including variable and fixed costs may show a more homogeneous standardized net revenue per vessel across the season.

Table VII.2
Vessel Effort, Revenues, and Profitability by Vessel Class for the Base Period

	Summers	Early-exiters	Highliners	Partakers	Misc.	Total
Vessels	96	38	36	84	67	321
Effort	469,208	92,270	215,561	324,450	305,665	1,407,155
Dec-Feb	263,740	92,270	164,773	255,265	265,248	1,041,296
Mar-Aug	205,468	0	50,788	69,185	40,418	365,859
Trips	3,086	403	865	1,891	1,489	7,735
200 tier	669	34	16	353	97	1,169
300 tier	1,384	130	187	1,024	546	3,271
500 tier	1,033	239	662	514	847	3,294
Total ($000's)						
Revenue	12,434	4,233	6,845	10,055	10,338	43,905
Profitability	7,440	1,844	2,819	5,998	4,152	22,251
Per effort						
Revenue	26.5	45.9	31.8	31.0	33.8	31.2
Profitability	15.9	20.0	13.1	18.5	13.6	15.8
Per vessel						
Revenue	129,526	111,407	192,424	120,311	153,313	136,958
Profitability	77,497	48,521	79,237	71,768	61,570	69,412

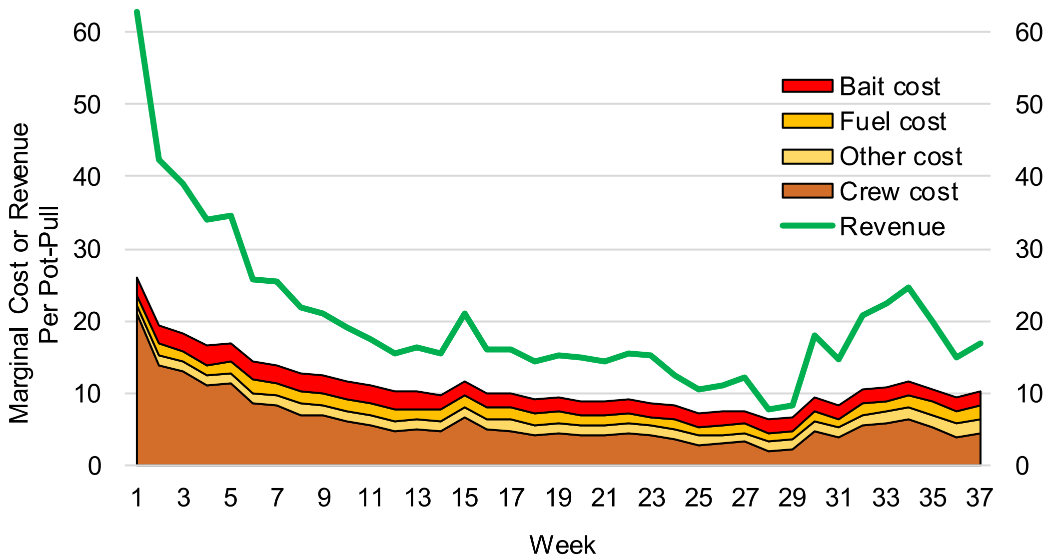
Notes: 1. The table tabulations are averages across the seven seasons in the base period.

Table VII.3
Crab Fishery Variable Costs by Vessel Class for the Base Period

	Bait Cost		Fuel and Other Cost Per Trip			
	Per Pot-Pull		Fuel			Captain
Classification	Dec-Feb	Mar-Aug	Type	Amount	Other	and Crew
Summers			low	$ 141	$ 149	26%
Early-exiters			high	$ 653	$ 598	39%
Highliners			high	$ 552	$ 299	39%
Partakers			med	$ 269	$ 197	26%
Miscellanies			med	$ 494	$ 598	39%
Total	$ 2.50	$ 1.88				

Notes: 1. Bait costs after February are for single bags.
2. Depth of fishing and vessel size determine fuel category assignment. Fishing greater distance (60 fm+) with longer vessel length (50 ft+) are "high" fuel costs (30% more). Fishing shallower (60 fm -) with shorter vessel length (50 ft -) are lower fuel costs (30% less).
3. Other costs are gear replacement, vessel maintenance, etc. and are greater (50% more) for high tier (500 pots) or lesser (50% less) for lower tier permits (200, 300 pots).
4. Crew/captain shares are after subtracting out provisioning and fuel costs.

Figure VII.1
Marginal Cost and Marginal Revenue by Week for the Base Period



Notes: 1. Revenue and cost are expressed in 2014 dollars. Dollar adjustment used the GDP implicit price deflator developed by the U.S. Bureau of Economic Analysis.

2. Marginal cost is variable cost per pot-pull. Cost categories are for crew, bait, fuel, and other costs. Crew costs are a share of the revenues. Bait is a cost per pot-pull expense. Fuel and other costs are a trip cost. The sum of each cost for each week over seven years is divided by the sum of all pots pulled over the seven years. Similarly, the crew share times the summed revenue over the seven years is divided by the sum of all pot-pulls over the seven years.

VIII. SEAFOOD PROCESSING YIELDS AND COSTS

Processor sector yields, allocation of purchased crab to different product forms, and processor operational costs for default conditions were derived from other studies (TRG 2015, Hankin et al. 2005) and were updated through key informant interviews. Interviewees provided information including the observation that crab yields increase and then decrease as the season progresses. However, there was not sufficient operational data to justify incorporating intra-season yield product variation within the model. Processor profitability is not included in the model for estimating impacts of management actions. Table VIII.1 shows the annual processing yields and allocations to different product forms.

Market timing and processor yields are important factors for evaluating management scenarios such as shifting openings and closings or developing management approaches based on stock assessments or quotas that could change delivery schedules. Additional model development would be needed to more rigorously test management ideas that could significantly shift effort.[1] For example, shifting away harvesting for the early season regional holiday market for whole cooked crab may not necessarily generate greater benefits associated with more consistent "even-flow" landings. There is a traditional holiday market for whole cooked crab whose demand may not transfer away from the time period. Processors can move significant quantities of landed crab for the whole cooked product form because labor, packaging, and warehousing is minimal. Processor investments would be needed to handle the changed volume going to different product forms. On the other hand, if Dungeness crab quality is high and supplies are less variable, national and international markets could be developed to maintain higher prices. Hankin et al. (2005) provides other discussions about how to increase the fishery's net economic value.

Table VIII.1
Processor Annual Yields, Costs, and Product Forms

Product Form	Round Pounds (thousands)	Landed Distri-bution	Ex-Vessel Price	Yield	Processor Costs/Sales Price Per Finished Pound: Raw	Other	Sales Price	Finished Pounds (thousands)	Wholesale Value (thousands)	Value Added (thousands)
Whole cooked fresh	3,407	30%	4.03	92%	4.38	1.22	5.60	3,135	17,546	3,824
Sections frozen	1,704	15%	4.03	58%	6.94	1.42	8.36	988	8,264	1,403
Meat canned and frozen	2,271	20%	4.03	25%	16.11	5.17	21.28	568	12,084	2,936
Live	3,975	35%	4.23	95%	4.45	1.12	5.57	3,776	21,033	4,229
Total	11,357	100%	4.10	75%	5.50	2.01	7.50	8,467	58,927	12,392

Notes:
1. Other costs include labor, taxes/fees, other production costs, and contribution to margin.
2. Wholesale value is ex-processor sales.
3. Default distribution of pounds to product forms assumes 30% whole, 15% sections, 20% meat, and 35% live.

1. A management regime based on an individual transferable quota (ITQ) system would have an outcome for shifting delivery schedules. A more thorough bioeconomic model would need to be developed to evaluate output based harvesting rights including quotas for profit maximizing schedules, advantages for vessel safety, crew/labor effects, and community economic impacts. Stock assessments are not conducted for the West Coast ocean Dungeness crab fishery, therefore the typical quota based fishery management approach would not apply to this fishery. An ITQ could be designed around temporal effort constraints or territorial user rights.

(this page is intentionally left blank)

IX. EXISTING CONDITIONS AND TRENDS

Existing conditions and trends are described in terms of the following characteristics.

- **Catch and price trends.** Figure IX.1 shows weekly adjusted prices for each base period season and the weekly price when averaged over all seasons during the base period. Prices generally rise from the season start until about Week 25 (corresponds to about the end of May). Prices fall after that week except there is a noticeable uptick the final couple weeks of the season. Annual volume varied between 12.3 million pounds in the 2007-08 season to 23.2 million in the 2009-10 season. Because of price trends, the annual ex-vessel revenue range (adjusted for 2014 dollars) followed a somewhat different pattern than the volume range. The low season was 2008-09 at $28.6 million and the high season was 2013-14 at $50.6 million.

- **Effort trends.** The data source is logbooks which is expanded based on submittal compliance and data sampling rate. Figure IX.2 shows harvest volume in relation to three indicators for each base period season: annual total effort, annual average catch per unit effort (CPUE), and annual soak days. Because harvest volume is the numerator, CPUE will trend with harvest volume as long as the denominator for effort does not change. Indeed, this is the case as shown in the total effort by season display. Participants tend to deploy their allowed tier's pots regardless of the harvest trend. The number of days between pot-pulls or soak days does not necessarily follow harvest trends. Soak days are higher in the spring and summer when biomass and effort is lower. This is reflective of rational economic behavior to lower trip making costs.

  Figure IX.3 shows weekly vessel effort variability envelope (one standard deviation) for each base period season and the average variability for the base period. Variability is high to start the season when all vessel classes are participating and falloff as the season progresses when participation is more homogenous. Figure IX.4 shows pot-pulls and CPUE by month for the base period. Figure IX.5 shows pot-pulls by vessel permit tier per week for the base period. The trend shows several times more pots being pulled than the tier allows at season start which decreases to about the tier number being pulled once per week at season end. Figure IX.6 shows average soak times by calendar month for the base period. The increasing trend for monthly soak times as the season progresses is consistent with the trends showing on the display for decreasing number of pots being pulled. Figure IX.7 shows base period weekly cumulative catch and cumulative effort. Half of the catch was landed between Weeks 2 and 3 which corresponds to 25 to 33 percent of a seasons total effort.

- **Other fisheries participation.** Most participants in the Dungeness crab fishery also participate in other Oregon fisheries. There are many combinations of vessel fishing "portfolios" as shown in Figure IX.8. Vessels are drawn into other fisheries over the course of a year for numerous reasons, such as permit status, regulations, weather, stock abundance, and prices. During the season, most crab vessels do not re-enter the crab fishery after exiting but some vessels (principally crab-salmon-tuna and crab-fixed gear groundfish) will oscillate. Figure IX.9 shows the average annual revenue of participating vessels for the base period (by week of exit from the fishery) and the relative proportion of Dungeness crab revenues compared to other fisheries. The trends show that vessels exiting later earn proportionally more revenue from the Dungeness crab fishery than from their other fisheries.

- **Vessel class information.** The model calculates impacts and results for the five vessel classes as described in Chapter VII. Figures IX.10 through IX.12 display information for selected characteristics for each vessel class. Figure IX.10 shows two displays: the base period's average number of participating vessels by week and by class and pie charts showing the share of revenue and vessel numbers for each vessel class. The graph illustrates that "early-exiters" leave the fishery by week 10, and "summers" remain in the fishery until almost the end of the season. The pie charts show that relative shares of the "summers" revenue is proportionately less than the "summers" vessel numbers. The converse is true for the "highliners." Figure IX.11 uses a "sunburst" chart and associated table to show the average distribution of revenues by all fisheries for each vessel class. The vessel class "miscellanies" have the highest per vessel revenue from the Dungeness crab fishery and the highest total per vessel revenue. This vessel class is highly diversified across fisheries as are the "early-exiters." "Summers" and "partakers" have the lowest total per vessel revenue and a large majority of their revenue is derived from the Dungeness crab fishery. Table IX.1 and Figure IX.12 display the fleet's significant heterogeneity across key characteristics including pot tiers, vessel length, Dungeness crab fishery tenure, exit/entry dates, and delivery numbers.

- **Fishing intensity map.** Figure IX.13 shows annual pot-pulls within large ocean blocks adjacent to the Oregon and Washington coasts. The selected year for Oregon is the 2012-13 season. The year for Washington is unknown. The data for both states is from logbooks. The displays show relative concentrations of fishing effort. The displays also show landings in Washington from area-of-catch off the Oregon Coast as well as landings in Oregon from area-of-catch off the California and Washington coasts.

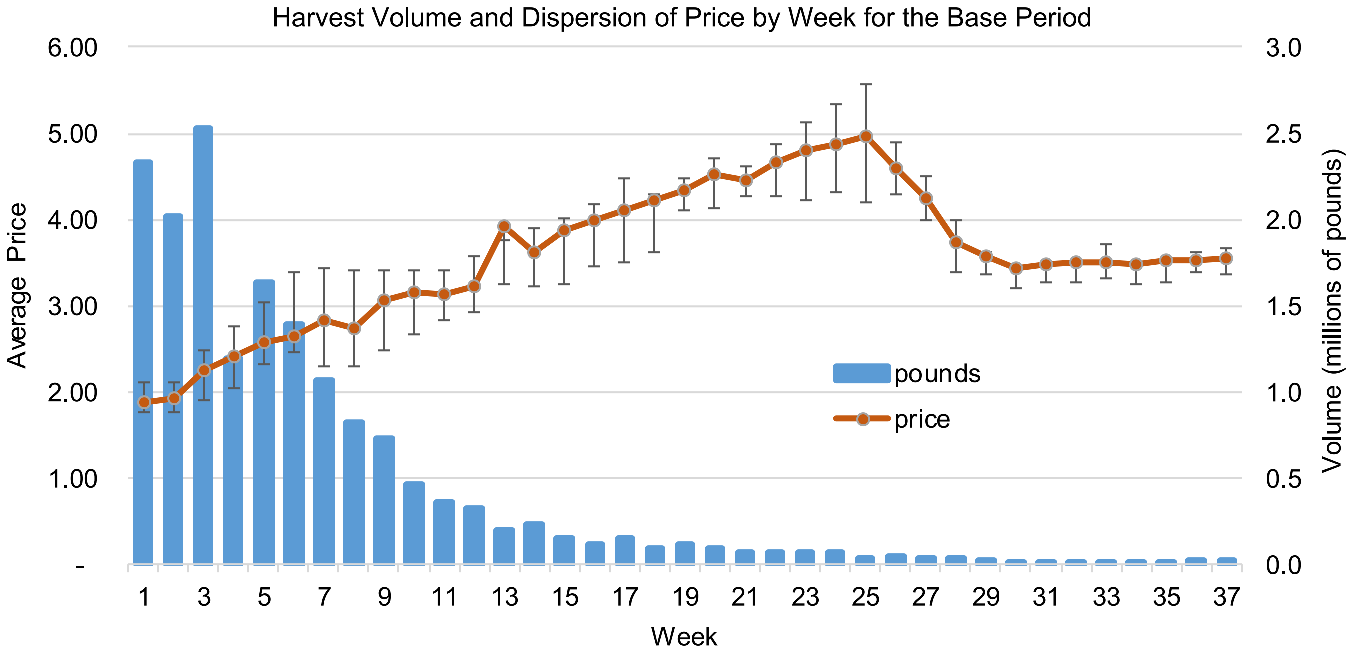
- **Effort by depth.** Figure IX.14 is a scattergram showing depth (fathoms) on the *y*-axis and week on the *x*-axis for every string pulled in the 2012-13 season. The plotted point (represented by a bubble) width is logbook hailed pounds. The season starts with a large variation in depth and gradually tends towards shallower depths. Testimony from industry participants indicated that the movement to inshore shallower waters is associated with the migration and availability of hard shell crab as well as avoiding pot placement in deeper waters fished by vessels using troll and trawl gear.

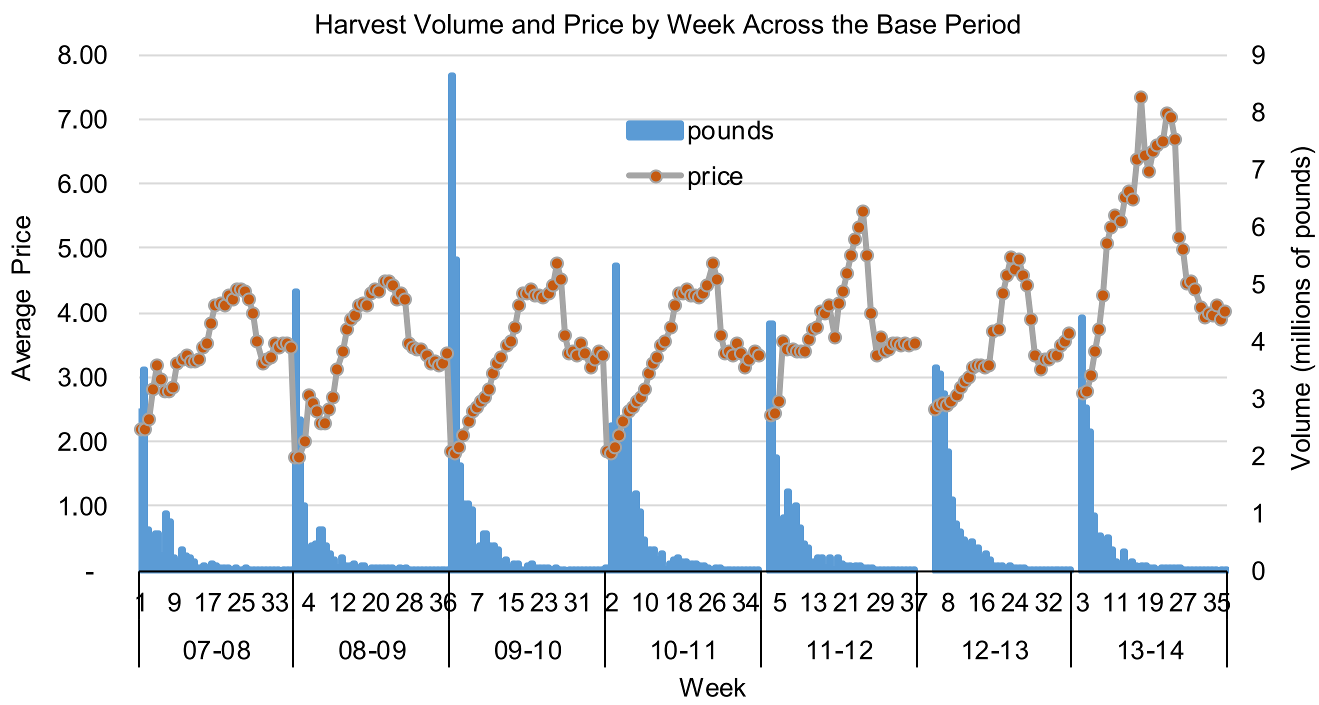
- **Vessel exit/entry.** Figure IX.15 shows monthly entrance and exit for the 2013-14 season. Nearly all participants (278 vessels) started the season in December and gradually exited as the season progressed. The display shows 11 new vessels entered in January, and lesser numbers entered over the following months. The 37 vessels fishing in August exited the fishery by the season closure date on August 14. While one season is shown, the entry-stay-and exit pattern is illustrative of all season in the base historical period.

- **Oregon fisheries.** Volume (pounds) and harvest value for recent years is shown on Figure IX.16.

  Table IX.2 shows the regional position of selected Oregon fisheries in the northern Pacific Ocean U.S. and Canada fisheries. For a comparison, Oregon's harvest value in 2014 was six percent of all Alaska, West Coast states, and British Columbia landings. Some fisheries have a higher harvest proportion, such as Dungeness crab at 19 percent in 2014.

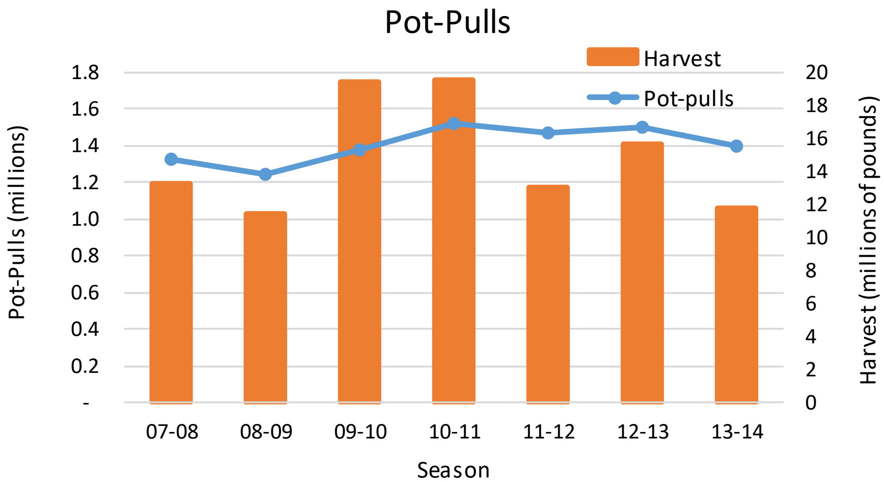
Figure IX.1
Catch and Price Trends



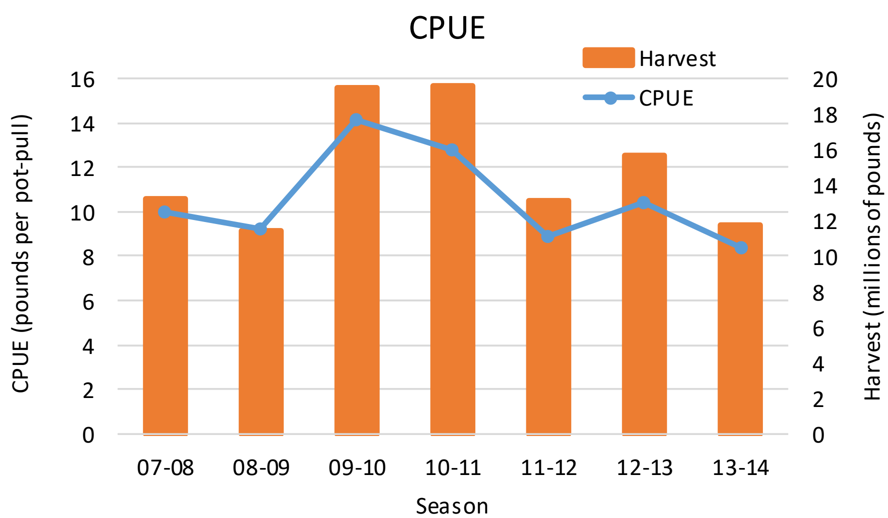


Note: 1. Price is in 2014 dollars.
2. First week starts December 1 for each season. Any landings after week 37 (which would be after season ending date August 14) are not shown.
3. Average weekly price line is the mean, and dispersion bars are the first and third quartiles.

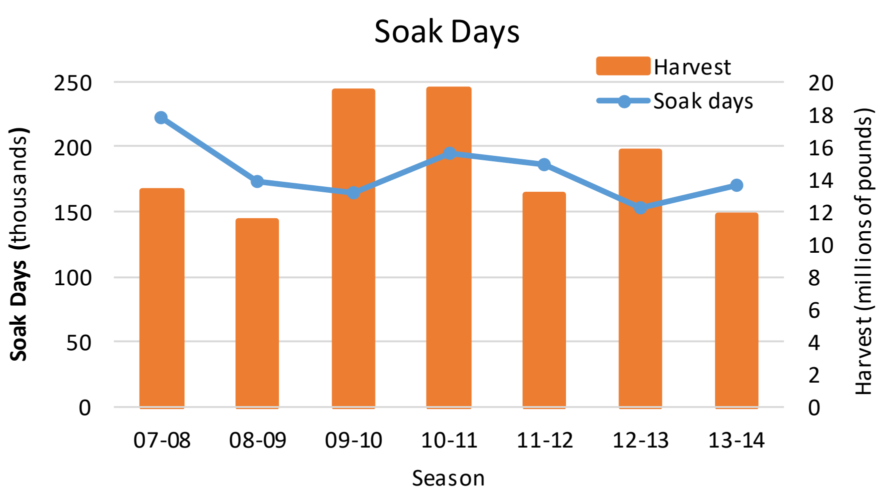
Figure IX.2
Annual Effort and Harvest Across the Base Period



Note: Logbook data expanded to represent 100% fleet.

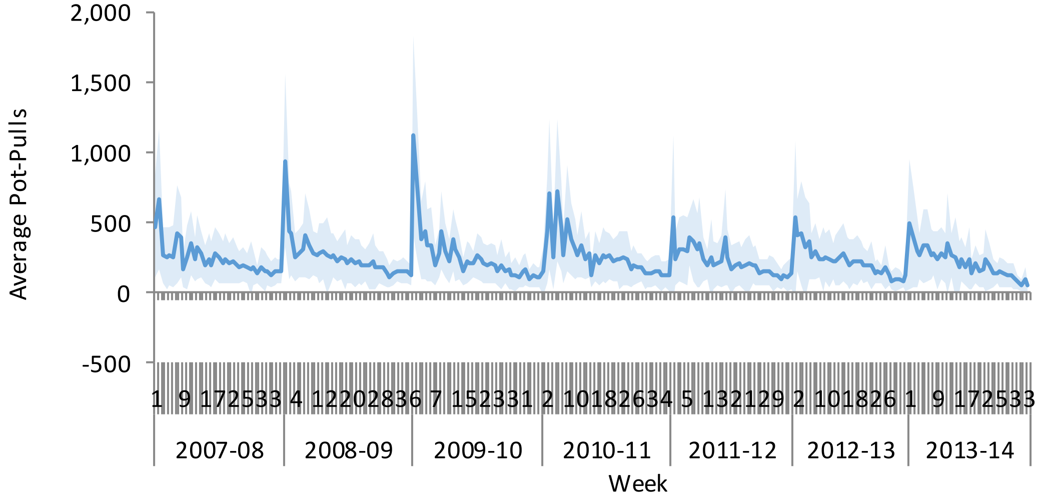


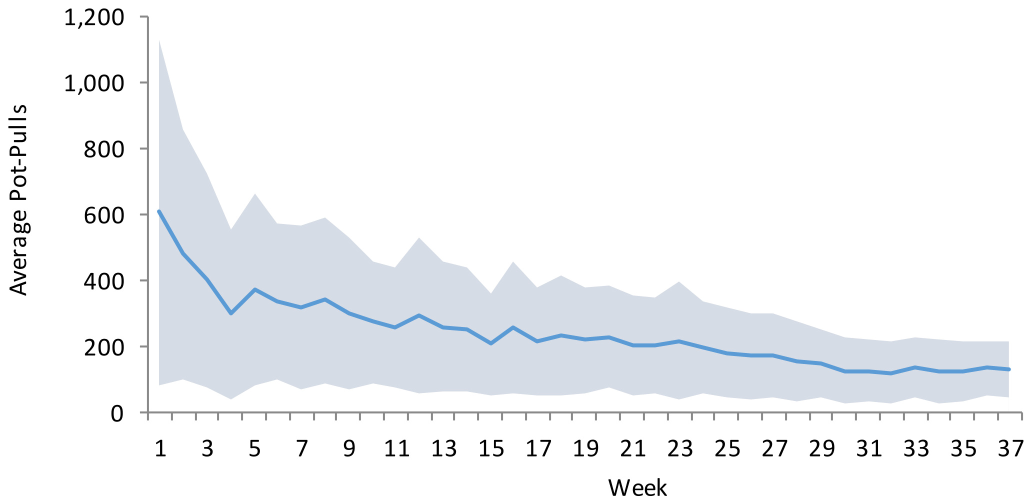
Note: Catch per unit effort (CPUE) is catch (pounds) divided by pot-pulls.



Note: Soak days are days between set and retrieve.

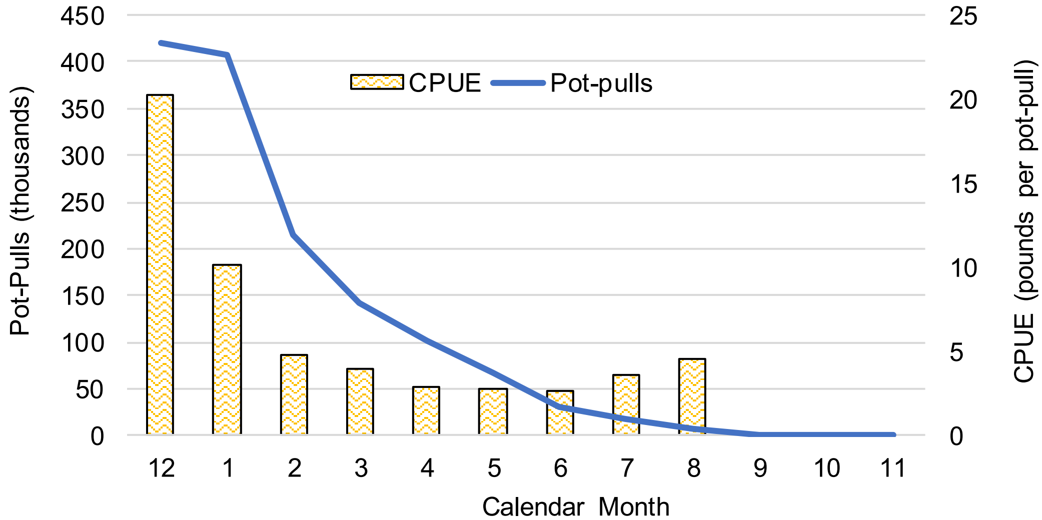
Figure IX.3
Effort Average and Variability by Week in Base Period





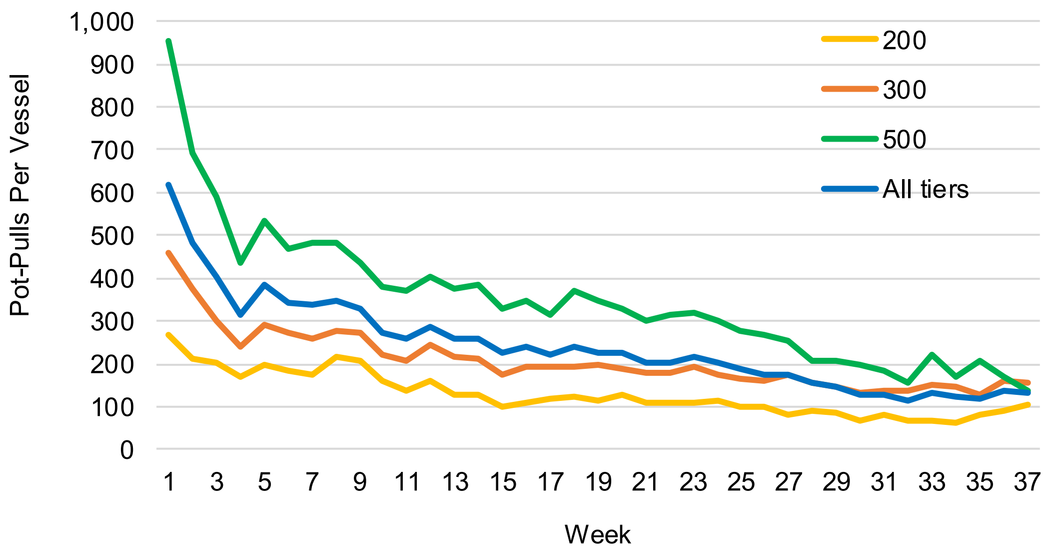
Notes: Envelope is +/- one standard deviation.

Figure IX.4
Pot-Pulls and CPUE by Month for Ocean Dungeness Crab Vessels in Base Period



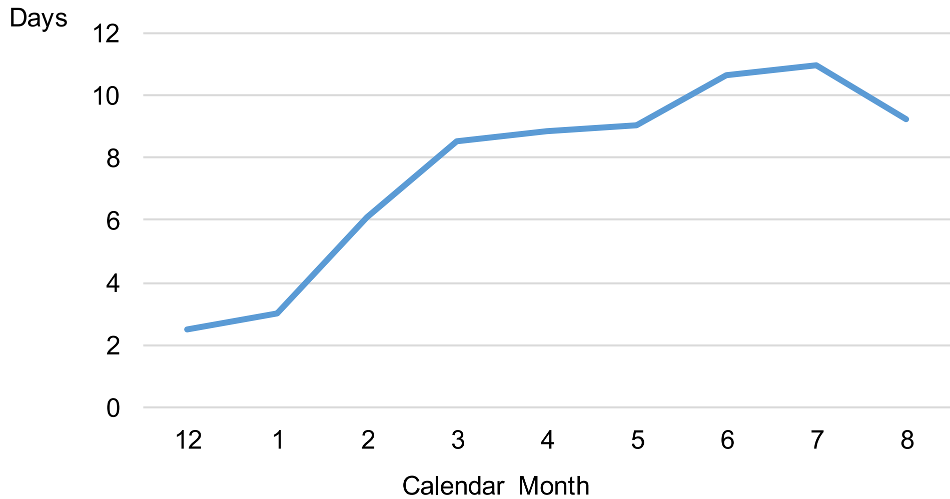
Note: Catch per unit effort (CPUE) is catch (pounds) divided by pot-pulls.
Source: ODFW crab logbook data, February 26, 2016 version.

Figure IX.5
Pot-Pulls Per Vessel by Week by Pot Tier for Base Period



Notes: 1. Week adjusted each year for season start.
2. Pots pulled per trip are defined to be all pots pulled on one day for one vessel.

Figure IX.6
Average Soak Time Per Pot Fished in Base Period



Note: Soak days are days between set and retrieve.

Figure IX.7
Cumulative Shares of Catch and Effort by Week for Base Period

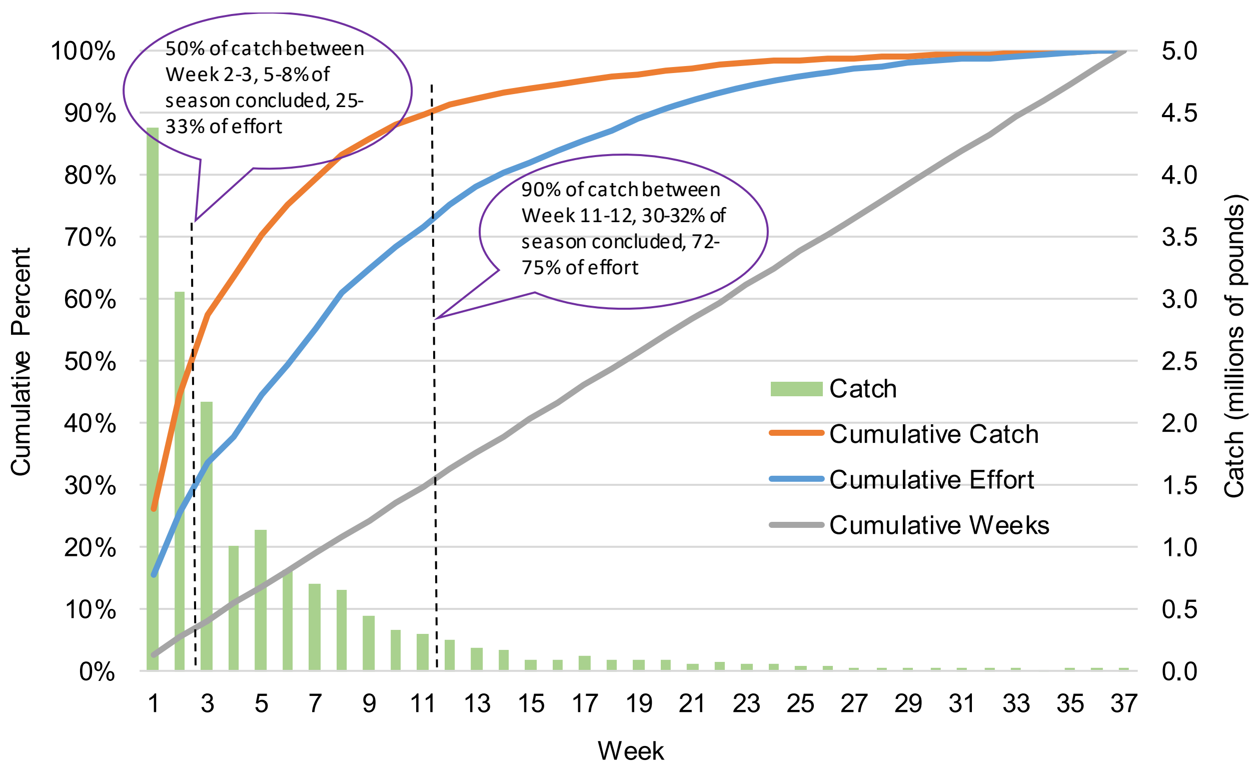
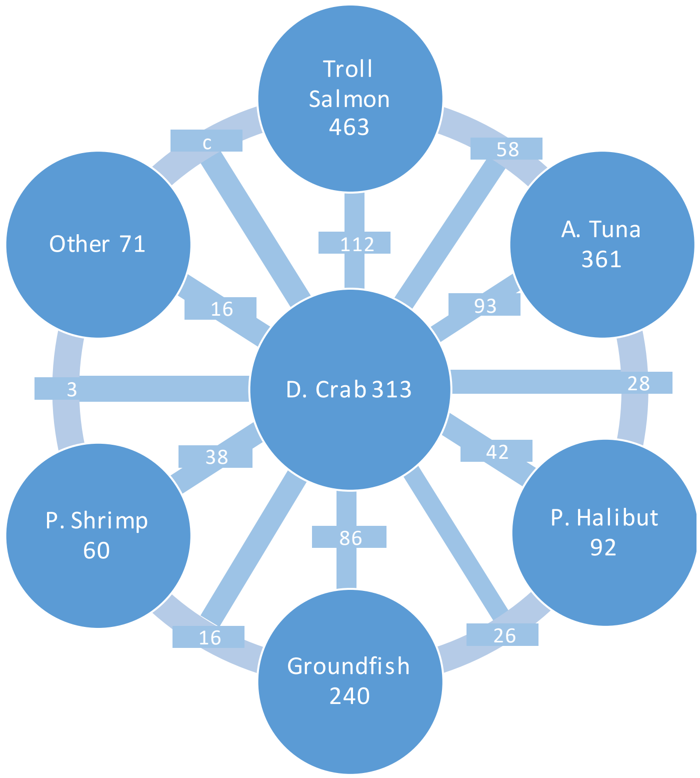


Figure IX.8
Vessel Counts by Active Fisheries Participation in 2014



Notes:
1. Active fisheries are defined as $500 minimum Oregon onshore harvest value, excluding research and discard disposition, for a vessel in each fishery. D. crab is for Dec. 2013 to Nov. 2014 season (excludes bay fishery), and all other fisheries are for calendar year 2014. The $500 filter should not be interpreted as an indicator for a vessel's targeted fisheries participation.
2. Vessels with identifier that starts with "ZZ" or "NONE" include tribal fisheries, and are not included in the vessel counts. Net salmon and bay D. crab are not included in "other." Other includes whiting, sardines, hagfish, and other species. Groundfish includes sablefish, soles, rockfishes, lingcod, and other species.
3. Vessel counts are not additive, because a vessel may participate in more than one of the defined fisheries. The figure shows counts for either one or two fisheries participation besides D. crab. There may be other fisheries combinations that a vessel participates which are not shown in the figure. For example, 26 vessels participated in ocean D. crab, troll salmon, and halibut. It is not possible to discern in this figure how many vessels participated in four fisheries. Examples of four or more fisheries:

Selected participation in ocean D. crab and three other fisheries:	
Troll salmon, a. tuna, P. halibut	18
Troll salmon, a. tuna, groundfish	16
A. tuna, P. halibut, groundfish	18
Selected participation in ocean D. crab and four other fisheries:	
Troll salmon, a. tuna, P. halibut, groundfish	10

4. Counts with a "c" are not shown to avoid revealing confidential information.

Figure IX.9
Participating Vessels Average Annual Revenue and Ratio Dependence on the Dungeness Crab Fishery by Week for the Base Period

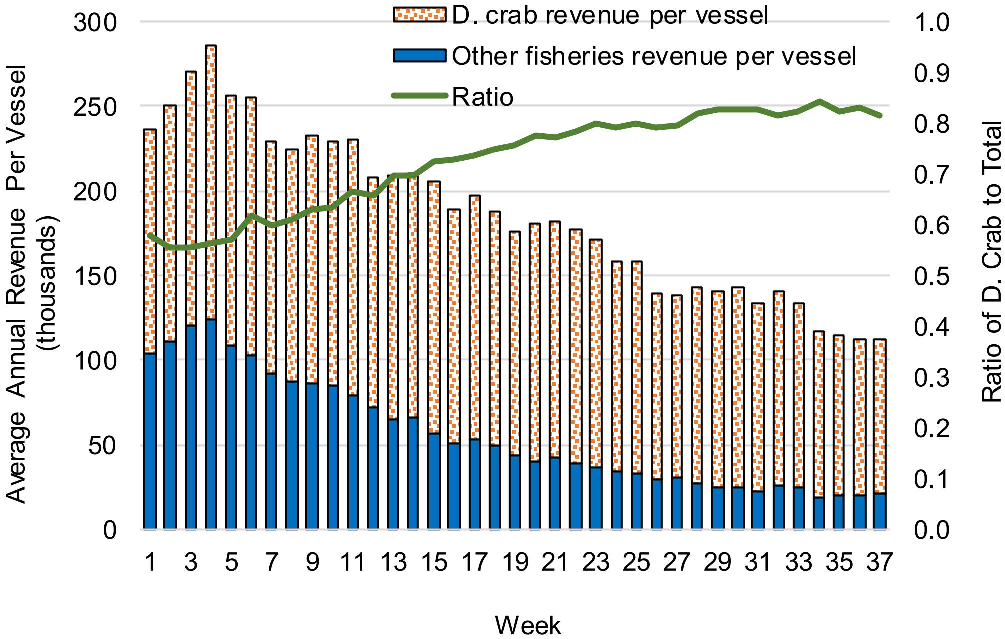
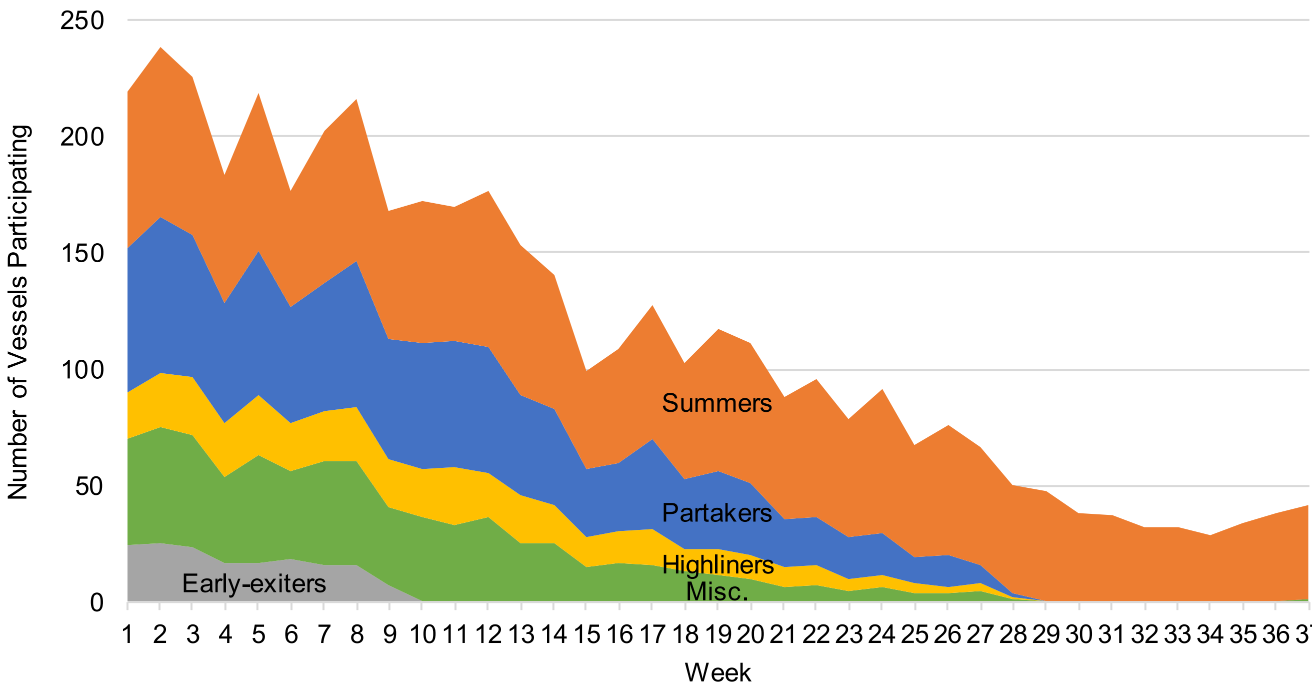
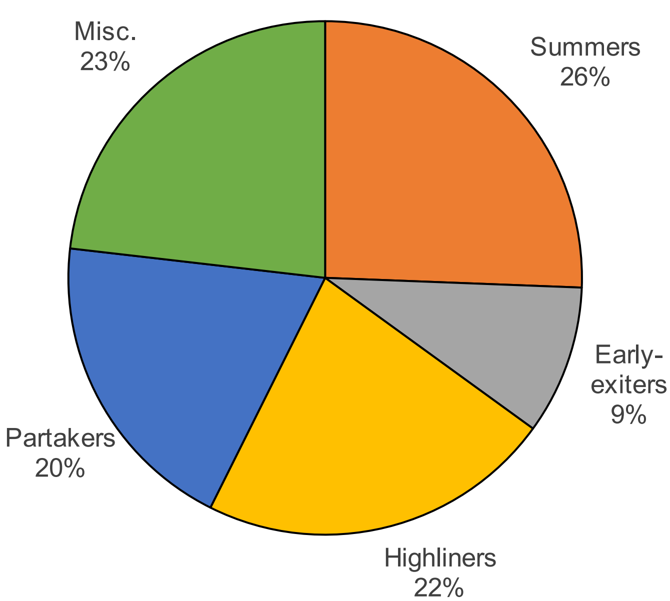


Figure IX.10
Vessel Participation by Vessel Class for Base Period



Shares of Oregon Ocean D. Crab Revenue (Real$)



Shares of Vessels

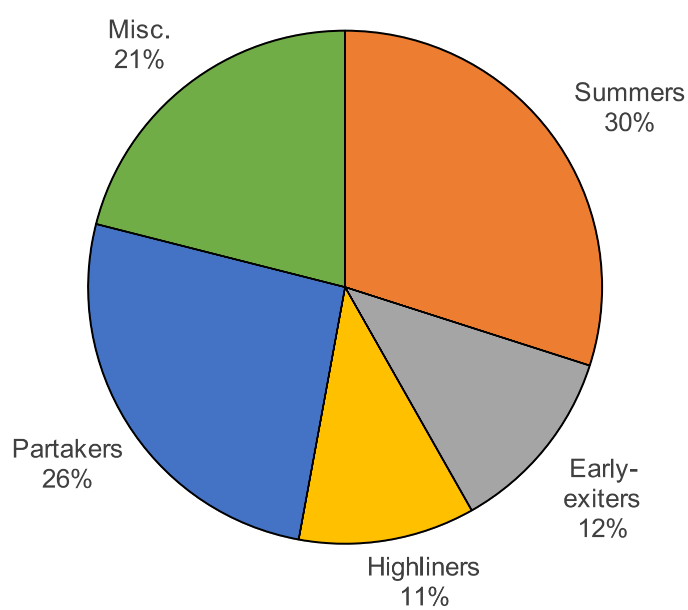
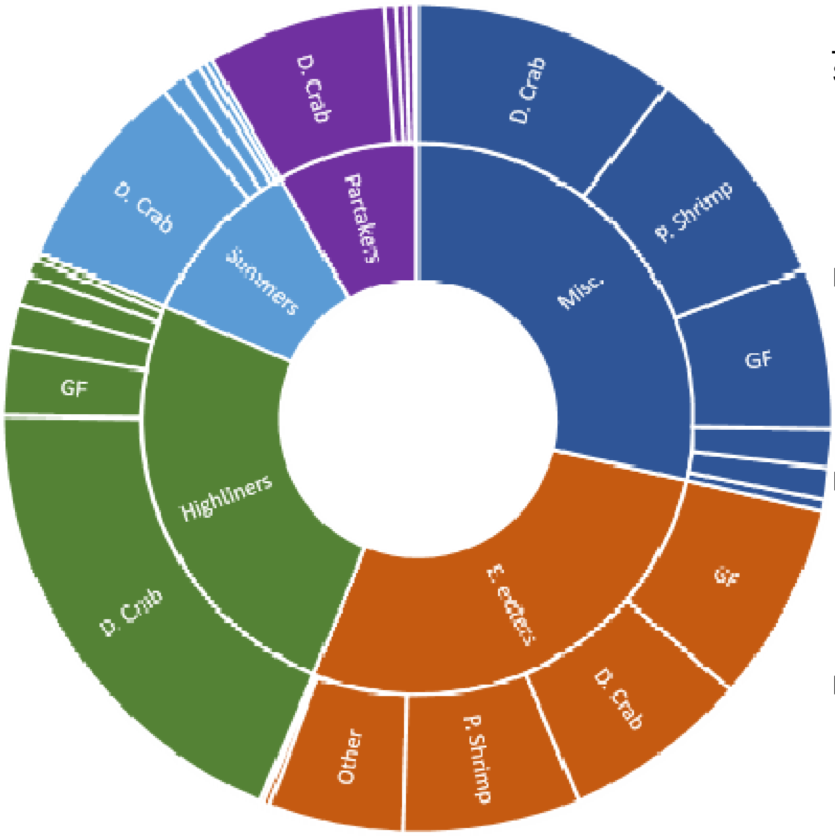


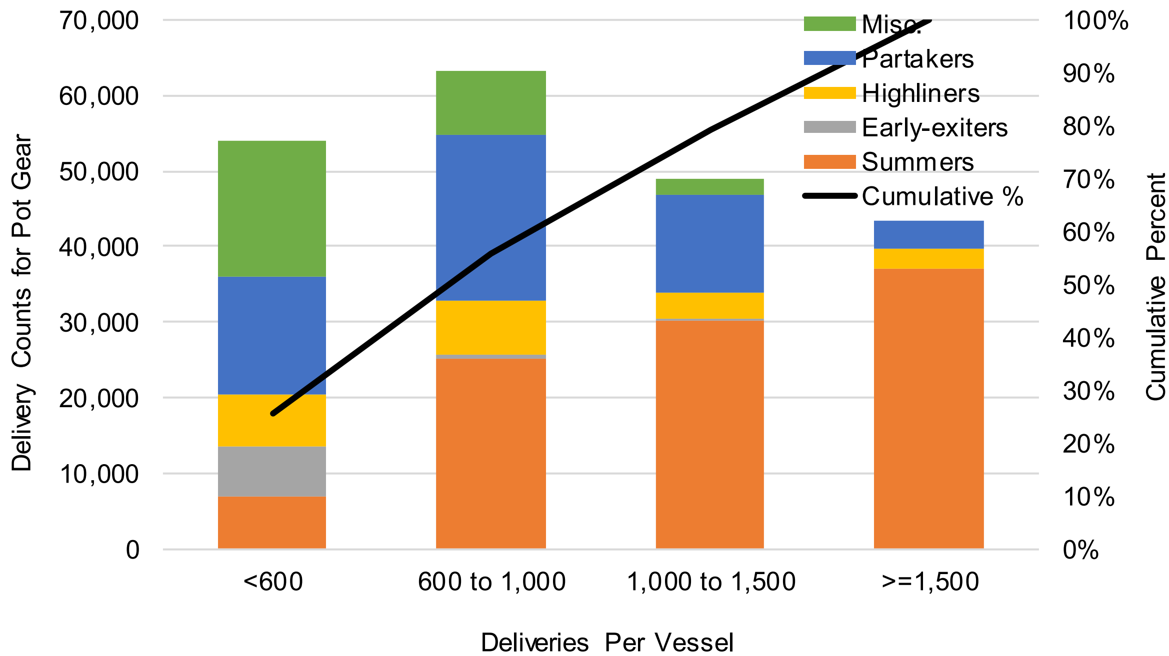
Figure IX.11
Vessel Class Other Fisheries Revenue for Base Period



		Per Vessel	
Class	Fishery	Average	Avg. Total
Summers	Salmon	4,252	
	D. Crab	110,584	
	P. Shrimp	233	
	A. Tuna	9,569	
	GF	12,629	
	Other	4,435	141,702
E. exiters	Salmon	1,862	
	D. Crab	101,873	
	P. Shrimp	95,857	
	A. Tuna	3,047	
	GF	107,708	
	Other	73,726	384,073
Highliners	Salmon	4,190	
	D. Crab	263,177	
	P. Shrimp	16,551	
	A. Tuna	22,500	
	GF	38,212	
	Other	9,380	354,010
Partakers	Salmon	5,442	
	D. Crab	96,271	
	P. Shrimp	508	
	A. Tuna	6,908	
	GF	4,247	
	Other	1,328	114,703
Misc.	Salmon	6,287	
	D. Crab	142,617	
	P. Shrimp	124,127	
	A. Tuna	17,571	
	GF	86,991	
	Other	20,775	398,369

Notes: 1. Vessel revenue for fisheries other than D. crab are averaged for calendar years of base period.

Figure IX.12
Frequency of Average Deliveries by Vessel Classifications for the Base Period

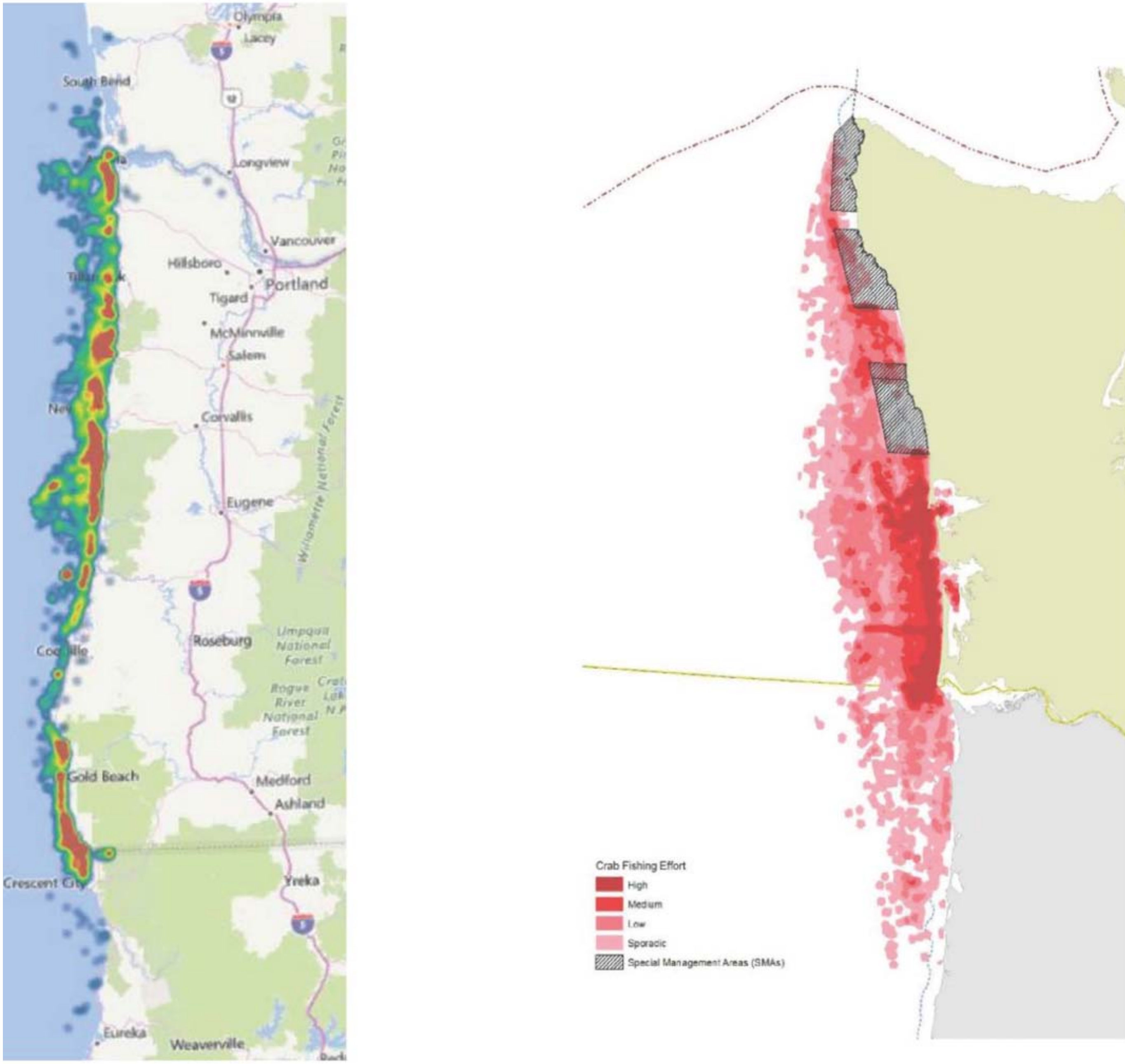


Notes: 1. Fish ticket data for harvests of ocean Dungeness crab uses gear code "CPT" as an acronym for crab pot.

Figure IX.13
Oregon and Washington Dungeness Crab Fishery Fishing Intensity Map

Effort Per Block in 2012-13 Season in Oregon

Effort Per Block Per Season for Landings in Washington

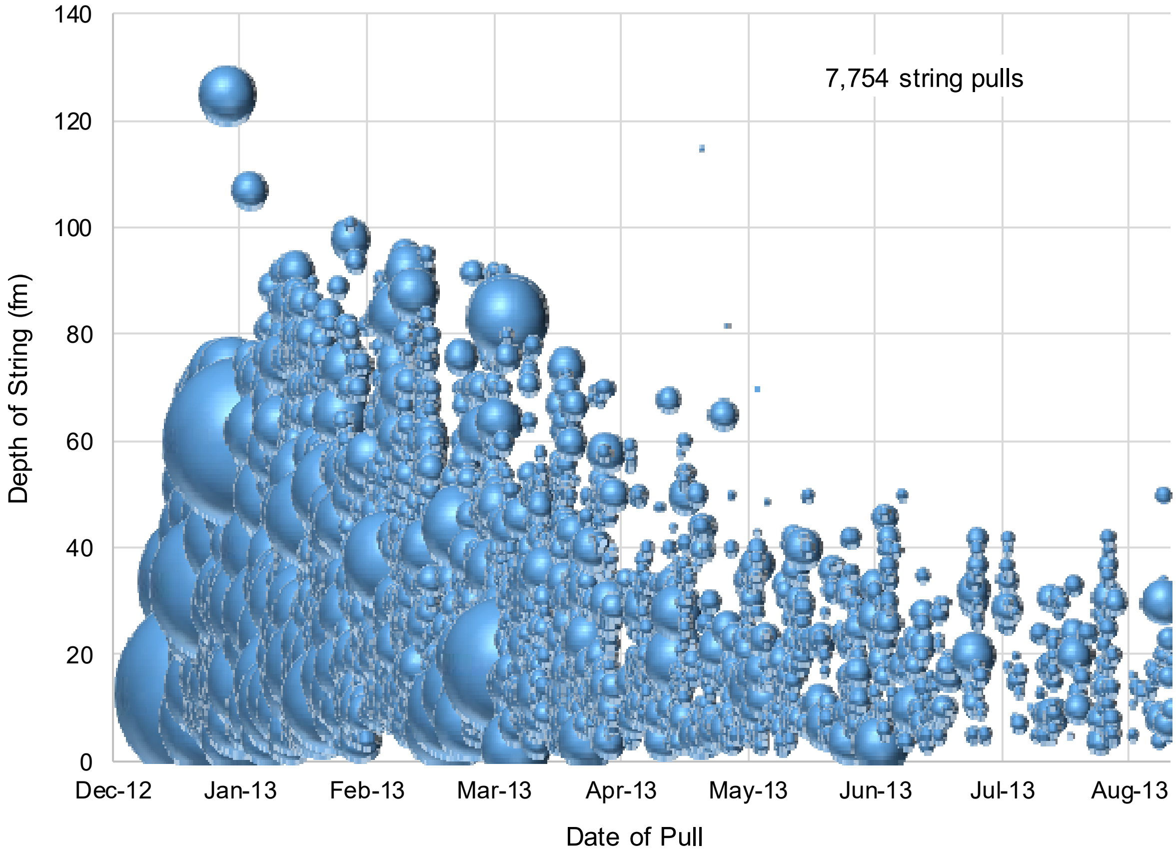


Notes: 1. Oregon ocean block size was 5 km and the season was 2012-13. The exact block size and season in Washington is unknown.

2. Total pounds of crab delivered in Oregon and harvested in Washington waters was 518,716 and harvested in California waters was 1,584,138 in 2012-13.

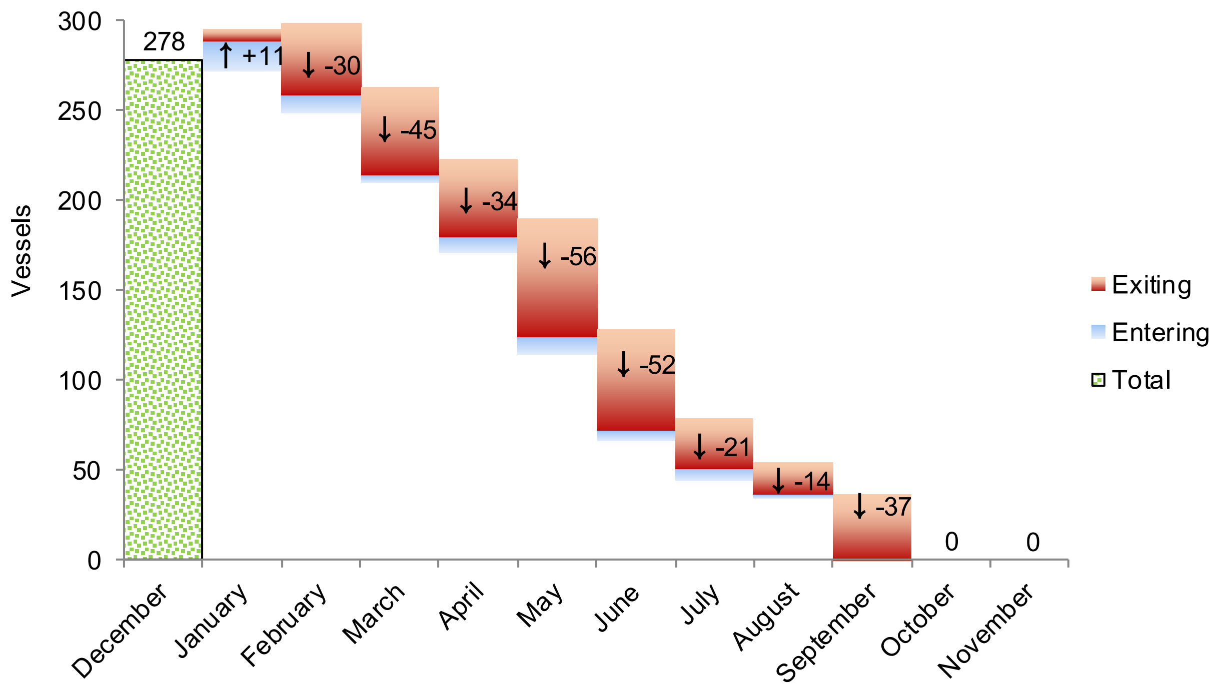
Source: ODFW and WDFW logbook information for example seasons.

Figure IX.14
Scattergram of Pot String Pulls by Date and Hailed Pounds in the 2012-13 Season



Notes: 1. Each bubble represents a crab pot string pull. Bubble radius is hailed pounds.
Source: ODFW crab logbook data, Feb. 26, 2016.

Figure IX.15
Vessel Exit/Entry by Month in December 2013 to November 2014

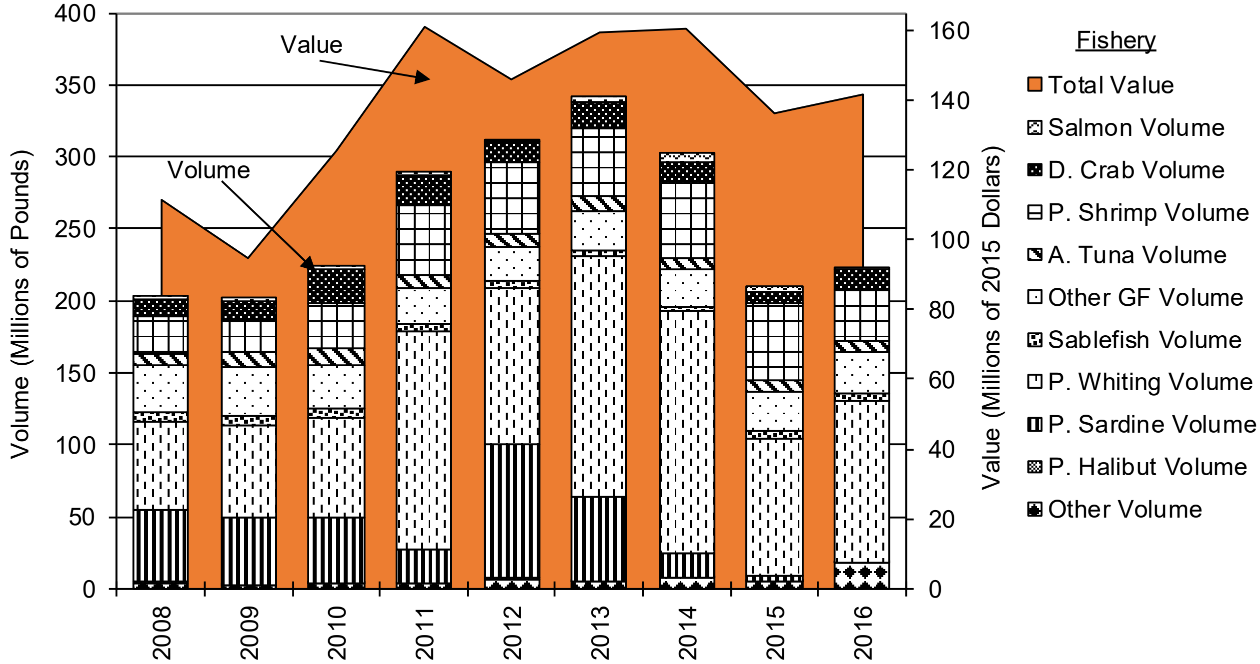


Notes:
1. Excludes vessels with identifier codes "ZZ…" or "NONE."
2. Excludes vessels using only gear other than crab pot gear (ocean) during the month, which is assumed to be vessels in bay crab or other fisheries with crab bycatch.
3. Excludes vessels that landed Dungeness crab with only research or discard disposition during the month.
4. Bars are annotated with beginning and ending month number of vessels, and net change in vessels for other months.
5. A vessel is counted as a "stay" during a month if it had at least one delivery of Dungeness crab using pot gear in the ocean or one delivery of Dungeness crab using other gear in bays.
6. The top of the blue bar shows the vessels continuing plus new entrants for the month. For example, there were 17 new vessels fishing in January that did not fish in December and six vessels that fished in December and did not fish in January. Thirty-seven vessels that fished in August did not fish in September.

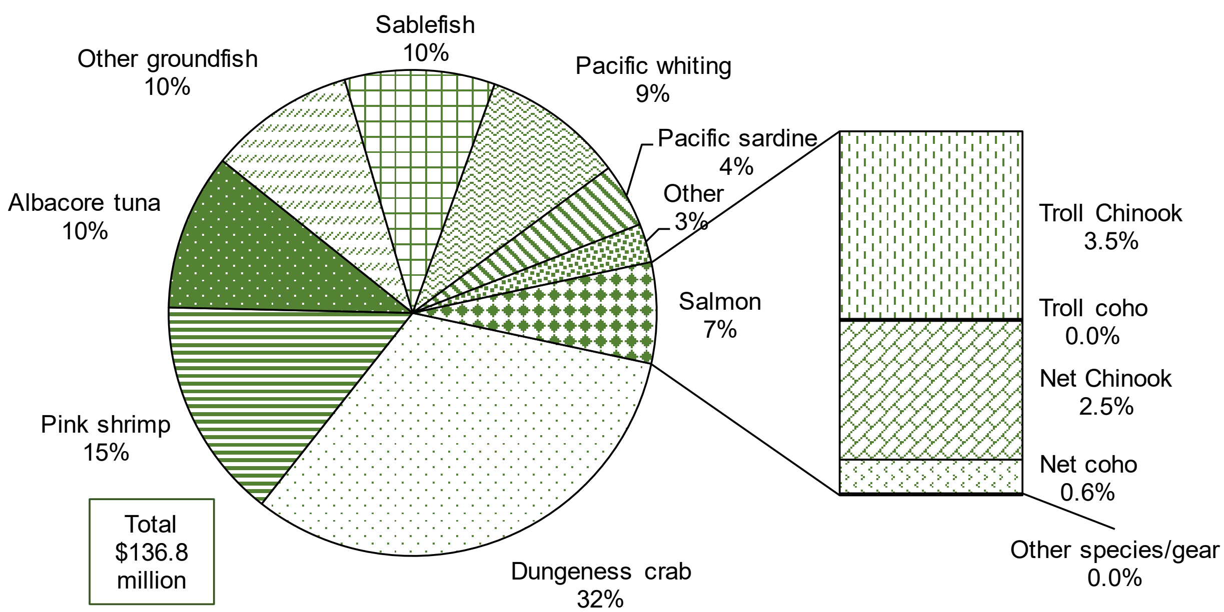
Source: PacFIN fish ticket data, March 2014 and April 2015 extractions.

Figure IX.16
Oregon Fisheries

Oregon Onshore Landed Value and Volume by Major Fishery in 2008 to 2016 (Preliminary)



Oregon Onshore Landed Harvest Value for Base Period



Notes: 1. Values are in 2015 dollars adjusted using the GDP implicit price deflator developed by U.S. Bureau of Economic Analysis.
2. D. crab is shown seasonally by December to November for each year, for example 2011 D. crab includes December 2010 to November 2011.
3. Deliveries are for onshore landings.

Source: PacFIN annual vessel summary and fish ticket data, April 2009, March 2010, July 2011, April 2013, March 2014, April 2015, and February 2016 extractions.

Table IX.1
Vessel Class Characteristics From Averaging Over the Base Period

	Count of Vessels							
	All Pot Tiers		Pot Tier 200		Pot Tier 300		Pot Tier 500	
Classification	Average	Coefficient of Variation	Average	Coefficient of Variation	Average	Coefficient of Variation	Average	Coefficient of Variation
Summers	96	0.11	26	0.13	43	0.16	27	0.18
Early-exiters	38	0.47	5	0.67	14	0.55	19	0.39
Highliners	36	0.41	1	1.38	7	0.82	28	0.33
Partakers	84	0.30	17	0.34	48	0.30	19	0.54
Miscellanies	67	0.29	7	0.38	26	0.44	35	0.28
Total	321	0.03	56	0.08	138	0.03	127	0.04

	D. Crab Share of Vessel Total Revenue		Vessel Length		Average Seasons of Participation
Classification	Average	Coefficient of Variation	Average	Coefficient of Variation	
Summers	72%	0.22	40	0.25	2.86
Early-exiters	21%	0.27	58	0.33	1.73
Highliners	56%	0.16	55	0.20	1.96
Partakers	89%	0.19	43	0.24	2.15
Miscellanies	28%	0.15	55	0.28	2.24
Weighted average	44%	0.21			

	Average Exit Day			Average Entrance Day		
Classification	Average		Coefficient of Variation	Average		Coefficient of Variation
Summers	234	Jul. 22	0.02	28	Dec. 28	0.46
Early-exiters	42	Jan. 11	0.13	18	Dec. 18	0.60
Highliners	132	Apr. 11	0.09	27	Dec. 27	0.53
Partakers	136	Apr. 15	0.06	19	Dec. 19	0.66
Miscellanies	115	Mar. 25	0.03	22	Dec. 22	0.51
Total	132	Apr. 11		23	Dec. 23	

Notes: 1. Total revenue is any West Coast fishery revenue in calendar year.
2. Average seasons of participation are weighted by vessel counts during the base period. Vessels with different classifications in different seasons are counted by the number of seasons the vessel participated in that classification.
3. Entrance and exit days are first delivery and last delivery day.

Table IX.2
Northern Pacific Ocean U.S. and Canada Harvest Value in 2014

	All Fisheries		Selected Fisheries					
			Salmon		Dungeness Crab		Trawl Shrimp	
Region	Amount	Share	Amount	Share	Amount	Share	Amount	Share
Alaska	1,712.2	63%	546.0	76%	16.0	6%	0.7	1%
British Columbia	353.7	13%	98.9	14%	42.3	17%	1.5	3%
Washington onshore	240.3	9%	38.9	5%	80.4	32%	16.5	31%
Oregon onshore	156.1	6%	20.1	3%	48.0	19%	29.3	56%
California onshore	233.3	9%	12.2	2%	65.1	26%	4.3	8%
West Coast at-sea	35.1	1%						
Total	2,730.8	100%	716.1	100%	251.8	100%	52.3	100%

Notes: 1. Values are in millions of U.S. dollars (nominal).
2. Alaska and Canadian at-sea fisheries harvest value are included in their respective table rows.
3. Alaska trawl shrimp is sidestriped shrimp harvested with beam trawl gear in southeast Alaska. The Alaska table's value is for harvest in the 2014-15 season using statewide price in 2014. Canadian trawl shrimp is mostly pink shrimp and sidestriped with some coonstripe shrimp and humpback shrimp. Table's values for Washington, Oregon, and California are all pink shrimp.
4. Aquaculture production is not shown in the table.
5. The all fisheries and selected fisheries harvest values except for Alaska trawl shrimp are for the calendar year.

Sources: Alaska and West Coast at-sea harvest value from NOAA Fisheries, Fisheries Statistics Division, Annual Commercial Landing Statistics (NMFS 2015), except Alaska trawl shrimp from ADFG commercial fishing information by area and by fishery. British Columbia harvest value from Fisheries and Oceans Canada (DFO), Economic Analysis and Statistics, commercial fisheries landings. West Coast onshore harvest value from PacFIN fish ticket data, April 2015 extraction. British Columbia harvest value converted to U.S. dollars using Bank of Canada exchange rates.

(this page is intentionally left blank)

X. BIOLOGICAL AND ECONOMIC RELATIONSHIPS

A. Relationships

A challenge for developing the bioeconomic model was not being able to rely on a science-based resource stock assessment. Heppell and Thompson (2010) explored stock size using equilibrium yield-per-recruit and age-structured population dynamics models, but concluded more data was needed to fully parametrize the models. Fishery dependent data, including from logbook and fish ticket systems, were available to develop simple biological relationships. Results from a new study by Yochum et al. (2017) provided a wealth of knowledge about resource reproduction biology, natural mortality, and handling mortality. The study was based on data acquired from ride-along trips with the Oregon Dungeness crab fishing fleet.

The bioeconomic simulation model was developed for Dungeness crab which is a single species fishery. More information about bioeconomic models used for single and multi-species applications can be found in studies such as Ives et al. (2013), Prellezo et al. (2012), Agar and Sutinen (2004), Larkin and Sylvia (2004), and Clark (1980). Those authors analyze and discuss bioeconomic models that evaluate management scenarios with goals to conserve fish stocks (e.g., as measured by spawning biomass) and social and economic objectives (e.g., as measured by harvest value).

One of the core drivers of the bioeconomic model was the behavioral relationships explaining the fleet's weekly fishing effort (pot-pulls). The relationship was estimated based on an empirical model of fishing effort estimated using the statistical regression technique of ordinary least squares. Logbooks provided data for estimating the dependent variable "effort" and several independent variables were postulated to have a major influence on effort including:

1) **Fishing Power.** The weekly number of participating vessels was selected as a proxy for fishing power. The fishing power predictor was hypothesized to be a measure of both competition (negative influence) and capacity (positive influence).
2) **Knowledge.** Catch per unit effort (CPUE) and ex-vessel price were combined into a single one week lagged variable (nominal revenue per unit effort (RPUE)) to represent knowledge with respect to trends in marginal revenue and economic performance of the fishery.
3) **Time.** The continuous time variable of time (weeks) was transformed to the power of 1.5 to account for any non-linear influences of effort across the season.

4) **Opportunity Cost.** The ratio of a vessel's revenue derived from the Dungeness crab fishery relative to a vessel's total revenue was used to represent opportunity costs associated with other fishing opportunities.[1]
5) **Riskiness.** Riskiness was defined to be landing variance per vessel.

Other effort predictor variables were considered but were not included for a number of reasons including availability and difficulty in standardizing data (e.g., weather, congestion, skipper experience, and market conditions).

Transformations of the dependent and chosen predictor variables were explored (e.g. log-log, log-linear, etc.), but regression result properties did not improve so a linear approach was used. Further, the chosen causation variables were not standardized (such as subtracting the mean); raw values were used for the regression.

Appendix A contains the statistical properties of the final regression equation and a pairwise independent variable correlation (Pearson product-moment coefficient) matrix. The regression equation high fit (adjusted R^2 accounts for 93.3 percent variation) can presuppose a multicollinearity issue. Multicollinearity can be a worry because small changes in predictor variable values can imply large differences in the fishery system. Only slight imprecision in predictor estimates may lead to inaccurate characterization of the fishery system. There were no additional explorations undertaken to reduce multicollinearity.

All regression coefficients have significance at the 0.05 level except the opportunity cost variable with a P-value of 0.55. The pairwise correlation coefficient for this variable is negative for all of the other predictor variables except the continuous time variable. The low significance of the variable may reflect participant ambivalence towards entering and exiting the fishery based solely on other revenue opportunities. This would be consistent with habit being a meaningful social/psychological factor in fishery choice models (Van Putten et al. 2012). Participants may enter the Dungeness crab fishery at season start and exit the fishery for other reasons including tradition and inertia (Bockstael and Opaluch 1983). Inclusion of this term in the regression results in effort having only partial elasticity relative to the opportunity cost variable. A 10 percent change in the opportunity cost variable value will cause a two percent change in predicted effort when all other predictors are held constant.

The equation residual plot shows heteroscedasticity (model errors are not uncorrelated and random) which may imply there are missing predictor variables. This is consistent with the high coefficient value for the continuous time variable that is absorbing the influences of missing or replacement variables.

1. The measurement is the percent change in the ratio of annual Dungeness crab fishery revenue to a vessel's annual revenue from all fisheries for vessels participating in the week. The annual revenue includes Dungeness crab for the season and other fisheries for the calendar year for Oregon landings only. (If a vessel landed Dungeness crab from the bay fishery or with research or discard disposition, the revenue is counted with other fisheries during the calendar year.) The percent change in the ratio decreases moving from later to earlier season weeks because the participating vessel class mix is less reliant on the Dungeness crab fishery for total revenue. The ratio is characterized as an indicator that compensating revenue being needed from other fisheries to maintain total vessel revenue.

The signs of the regression coefficients are positive for all predictors except the intercept variable. The signs make economic behavioral sense except for the riskiness variable which intuitively should be a negative predictor. Being positive, however, can be associated with derby fisheries characterized by rapid depletion of the available resource and where investments must be "protected" relative to other considerations (e.g., safe fishing conditions, operational efficiencies) (Branch et al. 2006). Harvesters will fish during times of high catch variance in order not to give up opportunities for high profit, especially at the beginning of the season.

Catch is estimated using the effort prediction, a time variant catchability coefficient, and biomass that is subject to decreases due to natural and fishing mortality and increases due to recruitment and growth. Economic measurements (harvest revenue, profitability, wholesale value, processor value added, and community economic impacts) are derived from the catch and effort predictions. For example, ex-vessel price is used to translate catch into harvest revenue. Effort and trips are used as the basis for estimating harvester variable costs. The community economic impact ratio estimators are from TRG (2015).

The relationships in algebraic form for the modeling approach are summarized below.

Each statistical week has its own effort predictor.

$E_t = \beta_1 V_t + \beta_2 R_t + \beta_3 O_t + \beta_4 S_t + \beta_5 t^{1.5} + I$ Eq. 1

where: E = predicted effort for a statistical week

V = vessels

R = revenue per unit effort lagged one week

t = continuous time week number

O = ratio of D. crab revenue to all fisheries revenue (annual)

S = riskiness (variance of effort by vessels)

I = intercept

β = regression coefficient

The predicted effort is used in a dynamic accounting approach to represent mature male biomass. It was assumed immigration and emigration netted to zero for the Oregon biomass.

$B_{t+1} = B_t + G_t - F_t - M_t$ Eq. 2

where: B_{t+1} = male biomass in the beginning of week t+1

B_t = male biomass at end of week t and at beginning of following season

G_t = recruitment at t=1 and zero for other weeks

F_t = fishing mortality pounds

M_t = natural mortality pounds

Fishing mortality has three components.

$F_t = H_t + C\&P_t + C_t$ Eq. 3

where: H_t = handling mortality

$C\&P_t$ (cannibalism/predation in pots)

C_t = retained catch

Handling mortality for four cohorts [sublegal soft (SS) and hard (SH) and legal soft (LS) and hard (LH)] is estimated from data collected in the Yochum (2016) study and the following smoothing relationships: Eq. 4

$$H_t = \sum_{k=1}^{4} \beta_k \exp(\alpha_k t) \cdot C_t$$

where: k = four cohorts

k	β	α
1 (SS_t)	0.000002	0.3187
2 (SH_t)	0.0038	0.0776
3 (LS_t)	0.000002	0.374
4 (LH_t)	0.00007	0.1561

Cannibalism/predation occurring in pots uses an estimate of soft crab present times a 6.8 percent mortality rate (Tegelberg 1972). A factor representing soft crab present in pulled pots is derived from Yochum (2016).

$C\&P_t = (SS_t + LS_t) * f * 6.8\%$

where: f = 5

Instantaneous natural mortality is from Zhang (2004). Eq. 5

$m_t = 1 - \exp(-1.25 / 52)$

where: m_t = proportion of male biomass that is natural mortality

Eq. 2 was rearranged using Eq. 3 to determine catch. The Gordon-Schaefer relationship qE_tB_t was substituted for C_t in order to solve for catchability q using linear programming.[2] Finding the solution used the Excel solver routine's Simplex option operating across the base period weekly catch and effort data. Priors were from Heppell and Thompson (2010) to specify initial conditions for biomass and catchability at Week 1, Year 1. First, an optimal solution for constant catchability was found by constraining the difference between calculated catch and actual catch to an error factor. Manual tuning seasonal pre-recruitment was used to reduce catch divergence.

Wilberg et al. (2010) instructs that fishery conduct superimposed on the fish resource life cycle makes a catchability term time varying. Solving for time variant catchability was accomplished by replacing the constant catchability with weekly CPUE divided by B_t. The catchability term's biomass is itemized in the current season to include pre-recruits and legal size crab, and itemized in the following season to include only legal size crab. Appendix B shows results for the current season constant catchability, time variant catchability, CPUE, and biomass.

Profitability is determined using harvest revenue and trip expenditures.

Eq. 6

$$NR_t = (C_t * P_t) - \sum_{i,j=1}^{i,j} S_{i,j}$$

where: NR_t = weekly average net revenue or profitability
C_t = weekly average retained catch

2. The relationship along with fishing cost considerations and stock logistic growth function is often attributed to the works of Gordon (1954) and Schaefer (1954) respectively.

P_t = weekly average price
S_t = weekly average spending (expenditures associated with effort and trips)
i,j = spending categories and vessel classes respectively

Fishery community economic impacts are estimated based on FEAM "factors" for harvester/processor "throughput" per pound. The factors are itemized to estimate marginal economic impacts from harvesters and processors. It is assumed perfect markets exist and processor variable costs and operation "contributions" are constant per finish pound processed which implies that processor "profitability" is not affected by product purchase price. Harvester marginal economic impacts are not constant and will swing proportional to the price used to develop the per harvest pound factor. The FEAM also provides a factor to transform marginal to average economic impacts.

$$L = \sum_{t=1}^{t} C_t \cdot \left[\left({}^{P_t}/_{P_c} \cdot LV_c\right) + (Y_t \cdot LP_c)\right] \cdot W_c \qquad \text{Eq. 7}$$

where: L = season average economic impacts measured by income at the state level economy
LV_c = the marginal economic impact (measured by income) per harvest pound for harvesting activities
LP_c = the marginal economic impact (measured by income) per finish pound for primary processor activities
P_t = weekly average ex-vessel price
P_c = annual ex-vessel price used to develop LV_c and LP_c
W_c = the ratio of marginal impacts to average impacts
Y_t = weekly yield

B. Measuring Community Economic Contributions

Economic contributions from the Dungeness crab fishery and calculations of economic impacts associated with management actions use a measurement for personal income based on landed pound ratios for harvesters and processors. Ratio estimators are from TRG (2015) and are explicit to Oregon's Dungeness crab fishery. These measures of economic effects use local spending by harvesters and primary processors that is generated due to the "value added" generated from harvester and processor actions. The ratio includes the so-called "multiplier effects" whereby the accumulated spending (after estimating "leakage" from the local and state economy) is included in the measure's calculation.

Personal income can be thought of as net earnings accruing to households in the region. The measure is translated to an equivalent job count using an average earnings level. Personal income is a reasonably comprehensible measure since individuals can identify with their own situation with respect to earnings and the additional jobs necessary to generate the estimated earnings.

There are other economic valuation measures that can also be developed to describe the importance of ocean resources. The measures selected for the Dungeness crab bioeconomic model focused on using an ocean resource for a well specified definition of activities. It is a focused and discrete calculation as compared to more abstract descriptions that include non-uses of ocean resources. The method also can be used to estimate impacts of other economic activities, which supports comparisons and tradeoff analysis used by policy makers to develop economic priorities.

In addition to economic effects, other social effects can be calculated and qualitatively discussed. These measures may pertain to how quality of life for industry participants and local citizens can be enriched from the improved management and investments in ocean resources. For this report, selected social indicators are used to develop tradeoff curves representing possible alternative management goals. The project would have to use redesigned methods and be repeated if other social and economic analysis measures were deemed necessary.

The measures of economic effects represent only the commercial ocean fishery harvester and processor sectors. This definition omits other fishery related spending associated with activities such as education, research, management, and enforcement. Vessel repair and facility maintenance is included in the effects, but construction (boat building, processor plant construction, associated moorage and waterway improvements, etc.) are not included. There are other Dungeness crab resource user activities also not included including commercial bay fisheries, recreational fishing, and treaty subsistence fishing. Finally, the Dungeness crab resource is an important species in the ocean ecosystem acting as both prey and predator. The economic impacts associated with the entire suite of Dungeness crab-related ecosystem services is also not included in this analysis.

C. Model Structure and Assumptions

Bioeconomic models are often designed to compare "net" social, economic, and biological benefits, i.e. the differences between status quo management actions and alternative management actions. This Dungeness crab fishery bioeconomic model, however, includes both net and "gross" fishery measures. The gross fishery measures are the net impacts added (or subtracted if net impacts are negative) to the base period measures. The stages of the model representing both net and gross impacts are shown in Figure X.1.

An option is offered to tabulate the results of a model run and export them to a new data file. This provides a convenient way for contrasting and comparing the economic impacts of two new alternative cases. For example, an analyst may be interested in understanding the economic impacts from a season delay due to meat yields. But what if the delayed season also had a different opening price? This would require two program runs. The output from each run can then be imported into a new spreadsheet created by the analyst to be used for further analysis.

Management action specifications can be used alone or in combination with assumption modifications to test alternative cases. Some changes in input parameters are percent differences of the default values (such as handling mortality component rates and current year prices) and others are absolute values (such as natural mortality). Cells adjacent to the slider and scroll bars controlling assumption values show the input variable values being changed.

Some of the equation terms in the model were developed for the project using statistical methods and others were borrowed from the literature. Whatever the source, assumptions had to be made about representing the "true" value. The model user is allowed to test these assumptions by altering (within limits) many of the model's parameters and coefficients. Appendix D shows result sensitivity for selected management actions and modeling assumptions.

The variables that can be modified are:

a) Biological
- Handling mortality (percent change of the ratio for cohort mortality to retained catch)
- Cohort mortality week shift (number of weeks shifted forward or backward due to biological conditions such as time of moulting)
- Natural mortality weekly factor (multiplication factor applied to biomass to determine mortality)
- Crab growth rate per year (percent change in growth pounds applied to current season's surviving biomass)
- Current and following season recruitment variability (percent change in beginning biomass)
- Catchability variability (percent change in CPUE per biomass in current season and per legal size biomass in following season), and catchability week shift

b) Harvester trip costs for each vessel classification
- Bait cost per pot-pull
  - Start of season through February
  - March to end of season
- Fuel cost per trip (average)
- Other cost per trip (average)
- Crew cost shares of revenue

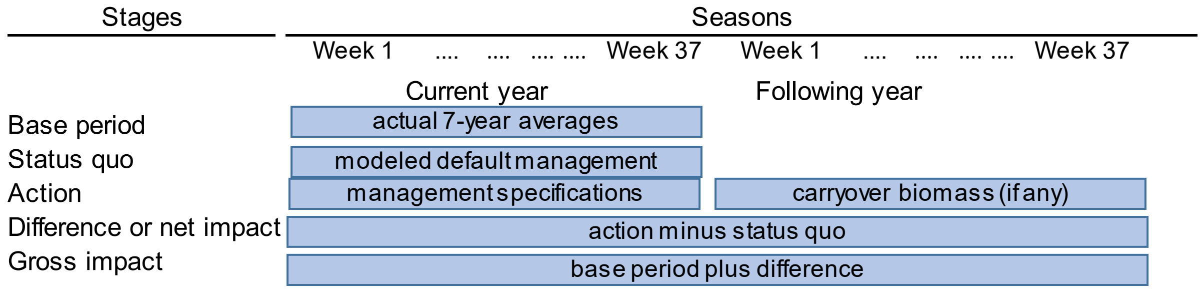
c) Season pattern
- Weekly price shift from base period in the current and following season. The slider bar controls the percent difference and an adjacent cell shows the corresponding starting price and season price due to the price shift.

d) Processor yields and product form proportions
- Yield (percent change) and proportion of purchases for product forms:
  - Whole cooked fresh
  - Sections frozen
  - Meat canned and frozen
  - Live

The management actions and model assumptions can be modified from the defaults within allowed ranges. The allowed ranges were devised to keep the calculations within a reasonable envelope of data variability. When using parameters borrowed from the literature, there may be associated confidence intervals that influence the range of the slider bars. The allowed ranges and the stages in which the inputs apply are shown in Table X.1.

The user may or may not have substantiated evidence for altering model assumptions. Instead a user may just want to hypothesize "what if" a biological or economic term was at a different level. In a sense, randomness is achieved by allowing the user to make input variable changes. Model developers can generate thousands of different combinations of model parameters based on their error structure to reveal uncertainties in assumptions and convergence in results. The approach is useful for systematically exploring risk, uncertainty, and sensitivity – especially for relatively complex models.

Figure X.1
Model Stages for Calculating Management Action Impacts



Note: Carryover biomass to more than one following year is very small and is not modeled.

Table X.1
Model Input Ranges

Menu Item Number	Menu Item Name	Default Value	Allowed Range	Simulated Year Change Applies
3.	Modeling Assumptions and Relationships			
a.	Biological terms			
i.	Handling mortality and growth rates			
1)	Handling mortality			
	Soft sublegal	0%	-30% - +30%	both
	Hard sublegal	0%	-30% - +30%	both
	Soft legal	0%	-30% - +30%	both
	Hard legal	0%	-30% - +30%	both
2)	Handling mortality week shift	0	-4 - +4	both
3)	Natural mortality factor per week	2.40%	1.73% - 2.88%	both
4)	Crab growth rate per year	10%	0% - 25%	following
5)	Current season recruitment variability	0%	-10% - +10%	current
ii.	Catchability			
1)	Catchability variability	0.0%	-10% - +10%	current
2)	Catchability week shift for delayed start	0	0 - 7	current
b.	Harvest economic terms			
i.	Trip costs			
1)	Summers			
	Bait cost per pot-pull			
	Start of season	$ 2.50	-50% - +50%	both
	March to end of season	$ 1.88	-50% - +50%	both
	Fuel cost per trip (average)	$ 141	-50% - +50%	both
	Other cost per trip (average)	$ 149	-50% - +50%	both
	Crew cost shares of revenue	26%	-50% - +50%	both
2)	Early-exiters			
	Bait cost per pot-pull			
	Start of season	$ 2.50	-50% - +50%	both
	March to end of season	$ 1.88	-50% - +50%	both
	Fuel cost per trip (average)	$ 653	-50% - +50%	both
	Other cost per trip (average)	$ 598	-50% - +50%	both
	Crew cost shares of revenue	39%	-50% - +50%	both
3)	Highliners			
	Bait cost per pot-pull			
	Start of season	$ 2.50	-50% - +50%	both
	March to end of season	$ 1.88	-50% - +50%	both
	Fuel cost per trip (average)	$ 552	-50% - +50%	both
	Other cost per trip (average)	$ 299	-50% - +50%	both
	Crew cost shares of revenue	39%	-50% - +50%	both
ii.	Season pattern			
1)	Ex-vessel price current season	0%	-50% - +50%	current
	following season	0%	-50% - +50%	following
c.	Processor terms			
i.	Yield (percent by product form)			
	Whole cooked fresh	92%	-10% - +8.7%	both
	Sections frozen	58%	-10% - +10%	both
	Meat canned and frozen	25%	-10% - +10%	both
	Live	95%	-10% - +5.3%	both
ii.	Product form proportions			
	Whole cooked fresh	30%	0% - 100%	both
	Sections frozen	15%	0% - 100%	both
	Meat canned and frozen	20%	0% - 100%	both
	Live	35%	0% - 100%	both
4.	Management Actions Specification			
a.	Altering Effort	0.0%	-10% - +10%	both
b.	Delayed Opening	0	0 - 7	current
c.	Early Closure	38	21 - 38	current

		Default Value	Allowed Range	Simulated Year Change Applies
4)	Partakers			
	Bait cost per p			
	Sta	$ 2.50	-50% - +50%	both
	Mar	$ 1.88	-50% - +50%	both
	Fuel cost per t	$ 269	-50% - +50%	both
	Other cost per	$ 197	-50% - +50%	both
	Crew cost shar	26%	-50% - +50%	both
5)	Misc.			
	Bait cost per p			
	Sta	$ 2.50	-50% - +50%	both
	Mar	$ 1.88	-50% - +50%	both
	Fuel cost per t	$ 494	-50% - +50%	both
	Other cost per	$ 598	-50% - +50%	both
	Crew cost shar	39%	-50% - +50%	both

(this page is intentionally left blank)

XI. MODEL RESULTS AND OUTPUTS

The model results are summaries for mature male biomass, natural and fishing mortalities, and many economic impact metrics. Output displays are tables and graphs sometimes containing intra-season and other times annual result summaries. Displays show both the status quo and the user crafted management action effects. A model output for the early closure management option is additionally shown in tradeoff comparisons between the crab resource and various social and economic dimensions stemming from early season closures.

A. Management Actions Specification

A user may want to craft a custom scenario for any of the three management options either singularly or in combination. Only summary results for the management analysis is shown within the action specification computer menu item. Full results are another menu option for model outputs. The crafted action specification is saved if a user wants to backcast results, i.e. jump back and forth making modeling assumption modifications and further specifying the management actions.

When specifying a management action, the user should keep in mind modeling methods. First, a change in modeling assumptions or management actions applies to both the current and following season years, except where noted on Table X.1. For example, a user could delay the current season, but the following season would open on the traditional start date. Another example would be vessel numbers are altered which affects both the current and following season.

Second, the change for altering effort is the percent difference in participating vessels in the fishery. Vessel numbers are an independent variable in the effort predictor that has a positive regression coefficient. A user selected percent lowering of vessel numbers will result in a lowering of effort and subsequent lowering of catch. However, it will be a non-linear effect because of the many other biological and economic relationships that come into play to calculate catch. For example, RPUE goes up when vessel participation goes down because of the ratio's denominator. One limitation for altering effort is that the adaptation of individual participants is not considered. For example, if the number of vessels was lowered such as through implementation of a permit buyout program, there could be less immediate congestion on the fishing grounds that would induce a non-buyout permittee to make more trips. Further, a permit owner that generally was not participating in the fishery could be drawn into participation, which would tend to restore congestion levels.

Third, the delayed season option effects are calculated using the weekly effort predictor equations. It is assumed some of the independent variables will have values as if the season start week is Week 1: riskiness, vessels, and RPUE. Catchability and price are also assumed to shift to Week 1. The independent variable values for harvester revenue opportunity assume the calendar week start. The model uses an algorithm to spread out the week number so that the independent variable values are evenly distributed across the structure of a shortened season. For example, this algorithm will preserve the usual price trend for starting low, increasing for about three months, decreasing to the end of the season, and ending the season with an uptick. A user may want to investigate raising prices in tandem with the season delay management option to mimic effects from harvest price negotiations (i.e. striking).

Fourth, the early closure option effects are calculated by eliminating the fishing mortality that occurs during the cut- off weeks. The retained catch and handling mortality that would have occurred is added back into the biomass and carried forward into the following season. The saved biomass is subject to natural mortality and an assumed size growth rate. Again, changes in individual behavior (such as vessel displacement to other fisheries to maintain total revenue) is not a model feature.

B. Model Result Ranges

This section summarizes the range of results for adopting new management actions. The results are shown for just management changes and are shown in combination with modifications to other model assumptions. The model does not alter prices from their normal temporal patterns but the model user has the option of shifting price to determine its effects on model outputs.

The management option ranges for the fleet and for each vessel classification are shown in Figures XI.1 to XI.3. The envelope for the low and high range was determined by modifying assumptions to achieve lowest and highest profitability.

C. Model Results for Eight-Week Early Closure

As an example, results for an eight-week early closure is shown on Figure XI.4. The model output is shown as the difference in weekly harvest revenues between status quo management and the implementation of the eight-week early closure.

The model results for beginning current year and ending current year biomass due to an example eight-week early closure is shown on Table XI.1. When the difference is negative, the saved biomass minus natural mortality is available to the fishery in the following year.

The model results for catch (pounds), harvest value, harvester profitability, wholesale value, processor value added, and community economic impacts are shown in Table XI.2. The weekly change in harvest revenue for the two seasons is shown in Figure XI.4. An eight-week early closure is used as an example for the figure.

D. Conservation and Economic Tradeoff Curves

Figure XI.5 shows several tradeoff curves comparing conservation and economic dimensions compared to harvester profitability associated with early season closures. Such curves are useful to decision makers who may want information about how biological and social effects track against changes in the economic and social performance of industry and community participants.

The dimensions of the tradeoff curves are selected to demonstrate effects to the "triple bottom line" associated with economic, community, and ecological sustainability (Anderson et al. 2015). The dimensions are harvester profitability (revenues minus variable costs) versus four other dimensions:

1) A conservation dimension is measured by the percent reduction in annual fishing mortality.
2) An equity dimension is measured by the percent change in annual vessel trips.
3) A community economic impact dimension is measured by the percent change in personal income at the state level economy. The driver of impacts is the spending by harvesters and processors to prosecute the fishery. Depending on the mix of the type of spending, there can be a situation where there is positive change in profitability but negative change in community impacts.[1]
4) A compensatory harvester revenue opportunities dimension is measured by the weekly participating vessels average annual Dungeness crab revenue divided by the participating vessels annual total fishery revenue. The ratio increases as the season progresses. A reduction in the ratio would be an indicator that there would be demand for compensating revenue from entering or heightening participation in other fisheries. Consequences to other fisheries are not modeled nor analyzed.

The tradeoff curves show the traditional non-linear and concave to-the-origin shape. Analysis by vessel classes shows that these trends are driven by losses to "summers" while other vessel classes are gaining in net revenue due to higher gains in the following year's season. Moving along the early closure lines shows the relative comparison for each dimension. For example, an eight-week early closure for the season (Week 30) would have a 0.4 percent decrease in profitability and a 1.8 percent saving in fishing mortality assuming default conditions for all other variables. If a model user were to change other assumptions in the model it would shift the position and shapes of the curves. The tradeoff curves help understand whether profitability as compared to the other potential fishery objectives increases and decreases relative to the status quo default conditions and the relative rate of change as management policies change. Results can inform decision makers with respect to the effects of instituting different management goals and objectives. Tradeoff curves are useful because they force consideration of economic gains or losses when other ecosystem services or social effects are being measured (Halpern et al. 2013). This is particularly important when the tradeoffs are significant and there are large gains/losses to the winners/losers. The bioeconomic model can be used to search for "optimal" policy solutions and "efficient" tradeoff curves that can better address economic and social objectives (Sylvia and Enriqeuz 1995).

1. Note that these curves do not incorporate all social considerations or how changes in production affect economic effects beyond the commercial fishery (e.g. seafood retail operations). While there may be decreased sales at seafood retail operations when there is not a satisfactory product substitute, there may be an incremental increase in economic impacts from recreational crabbing due to higher angler demand associated with higher resource abundance.

Figure XI.1
Profitability Impacts for Altering Effort

Profitability by Vessel Classifications

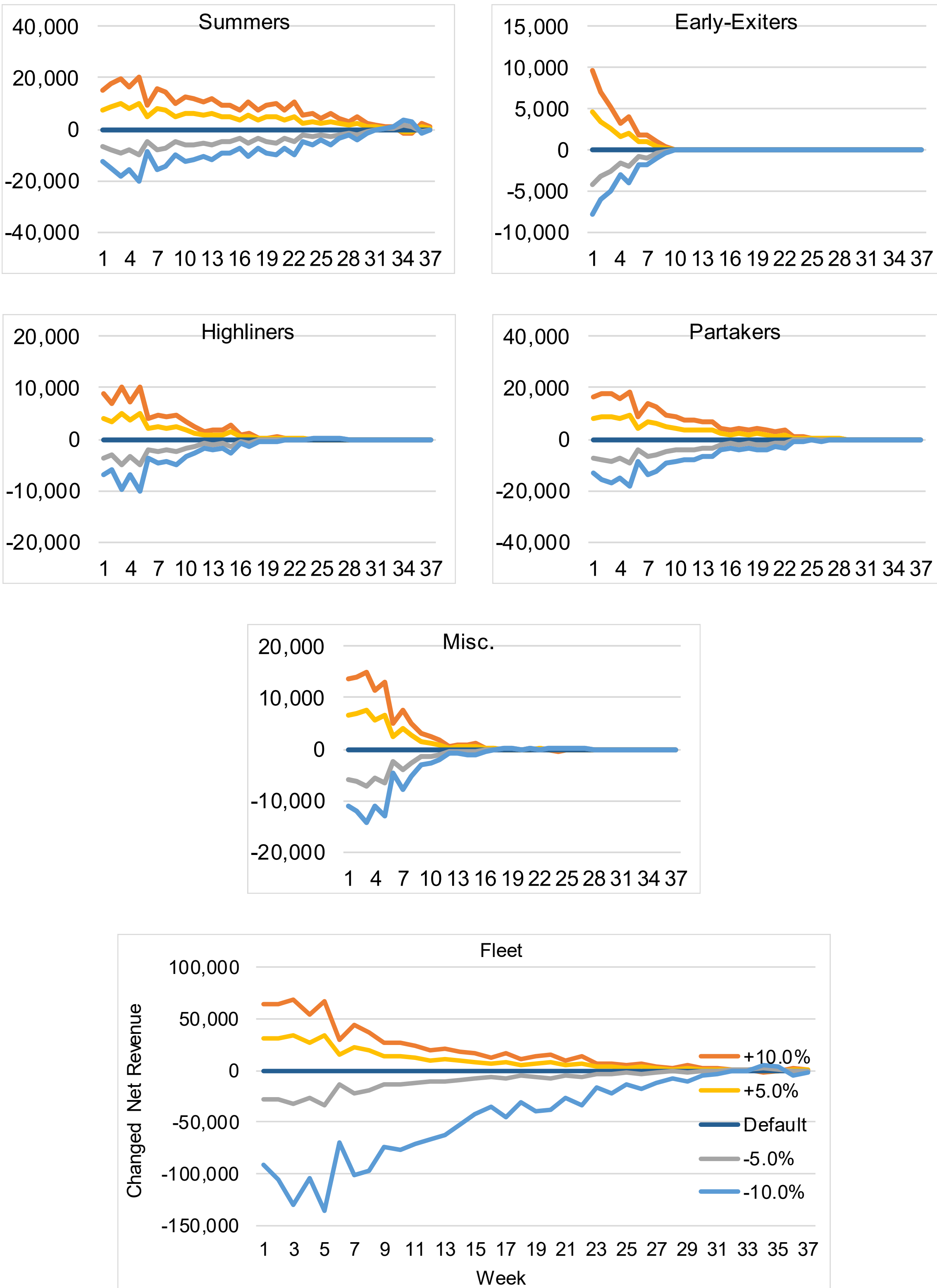
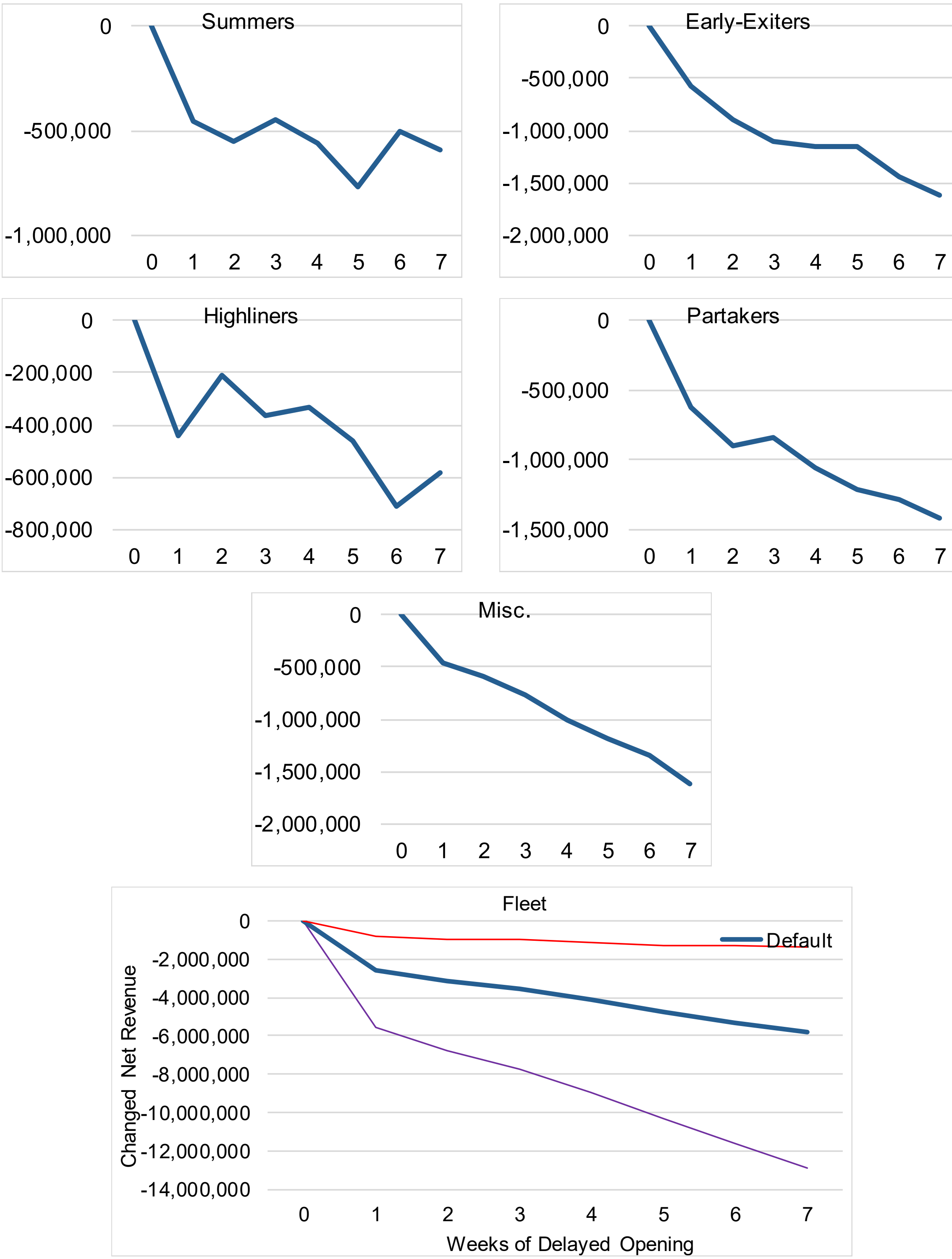


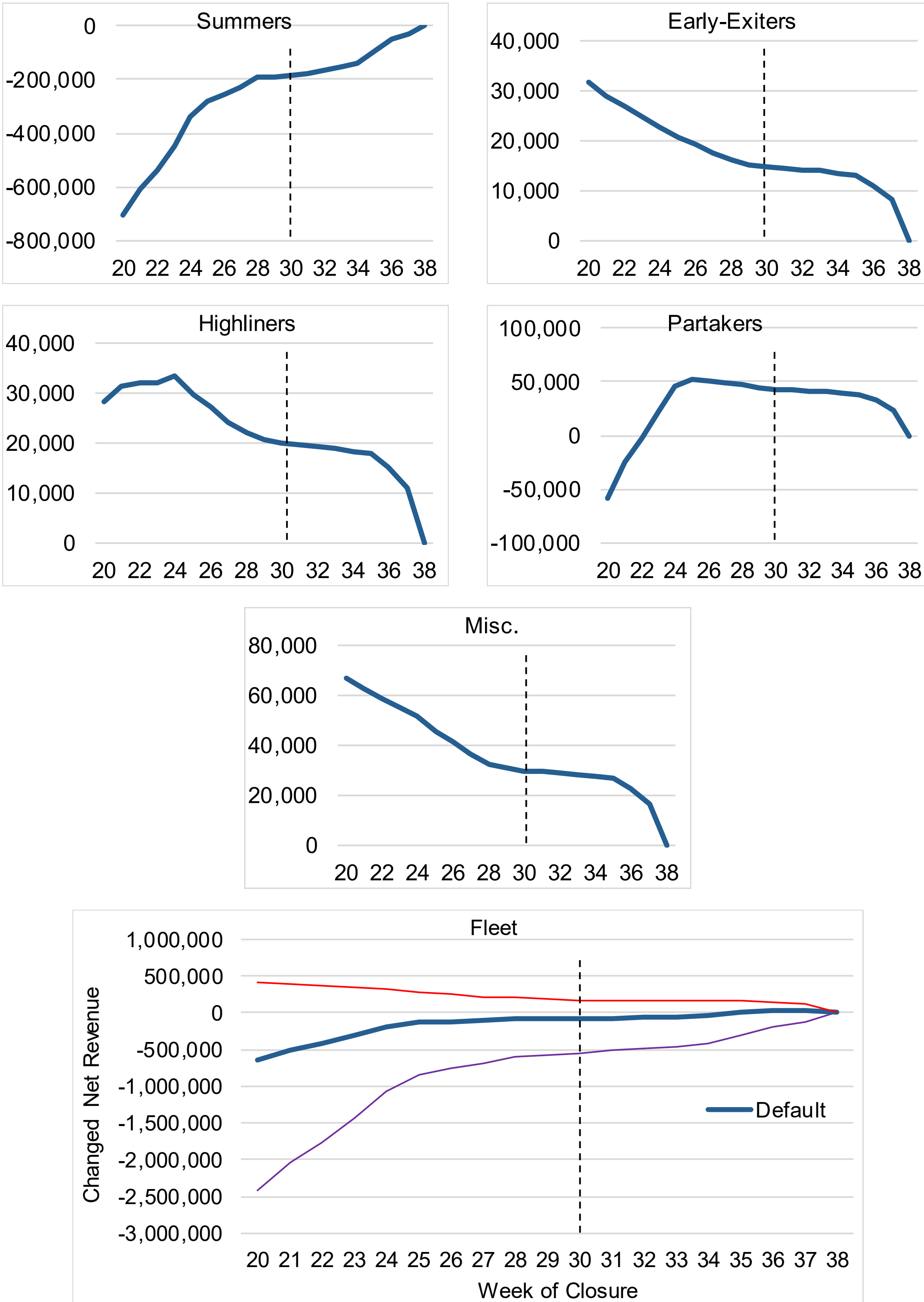
Figure XI.2
Profitability Impacts for Delaying Season Opening

Profitability by Vessel Classifications



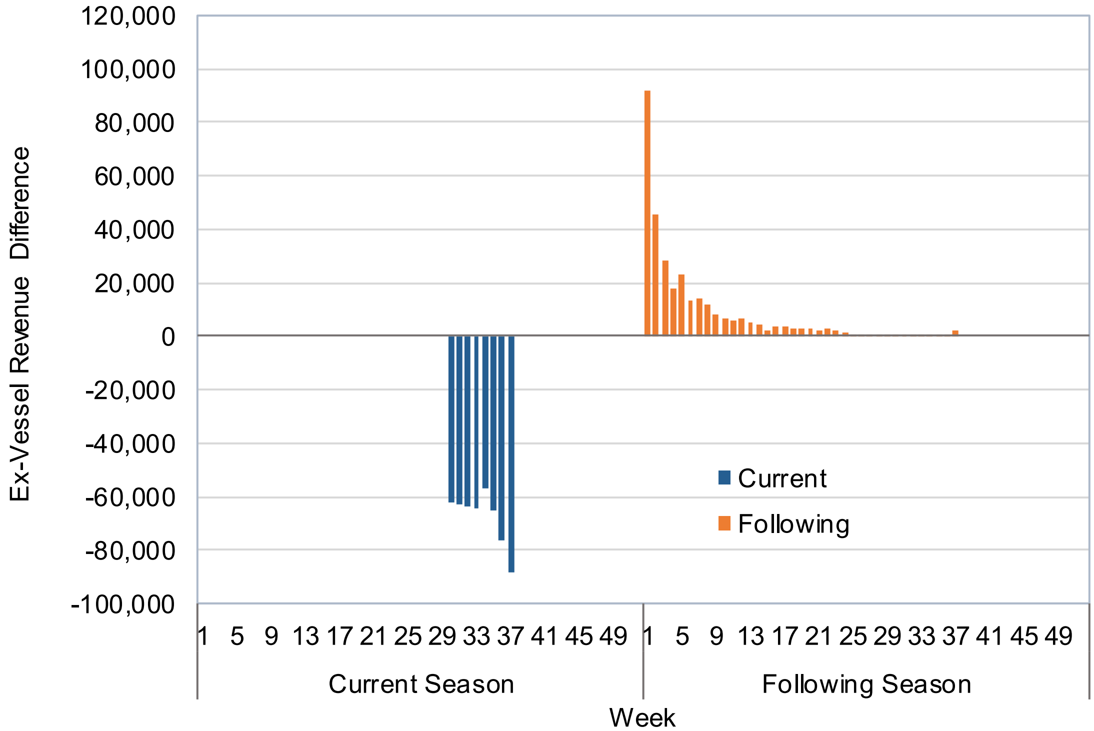
Notes: 1. High and low are dashboard status quo settings that maximize or minimize profitability at the end of the current season.

Figure XI.3
Profitability Impacts by Vessel Classifications for Early Season Closure



Notes: 1. The dashed vertical line shows season timing for an eight-week early closure.
2. High and low are dashboard status quo settings that maximize or minimize profitability at the end of the current season.

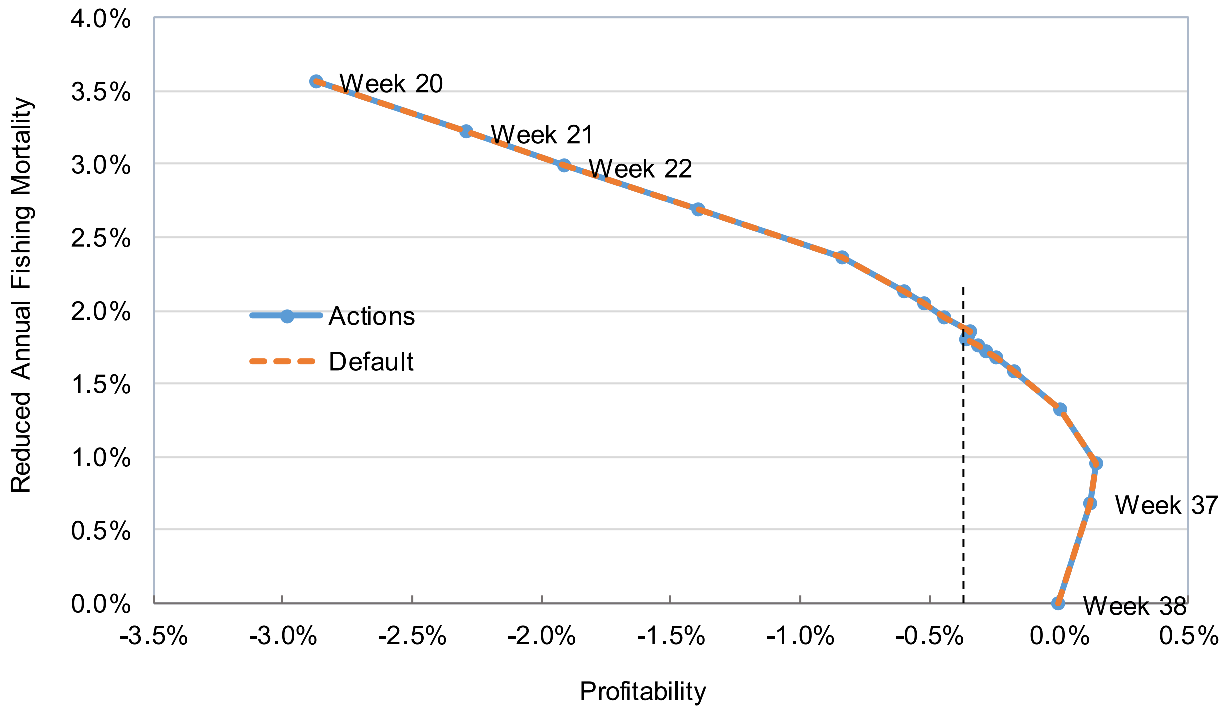
Figure XI.4
Harvest Value Weekly Difference for an Eight-Week Early Closure Management Action



Note: Difference is based on action minus status quo.

Figure XI.5
Management Action Tradeoff in Profitability Attained Through Season Early Closure

1. Conservation



2. Equity

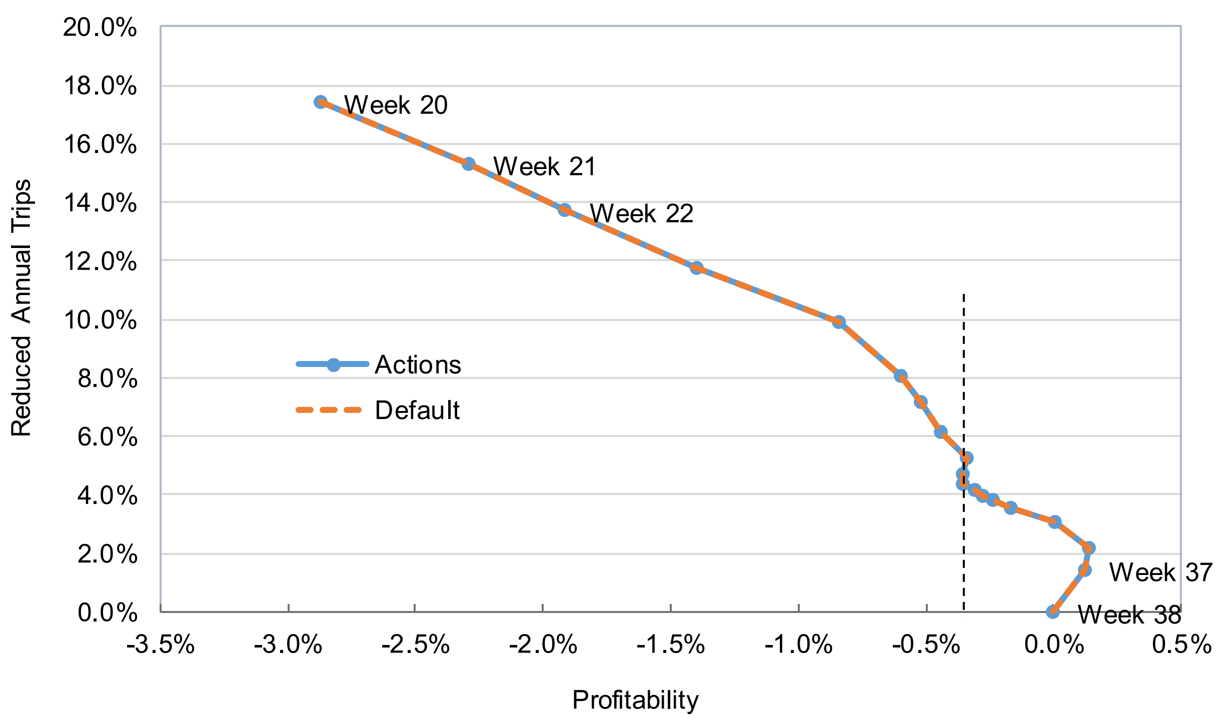
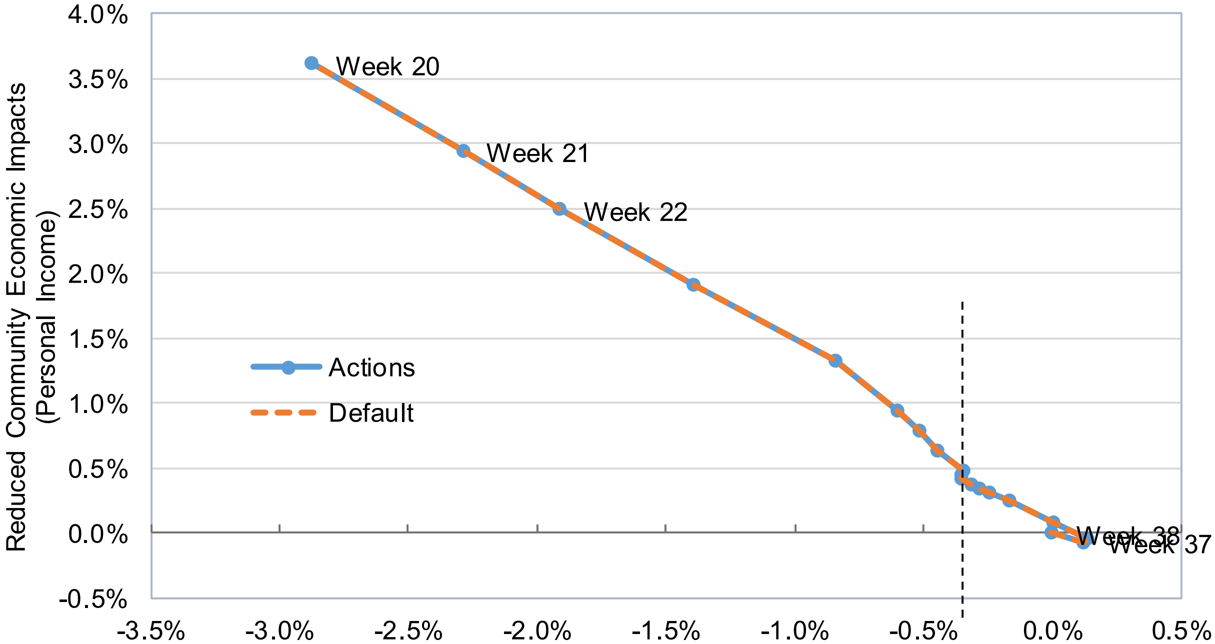
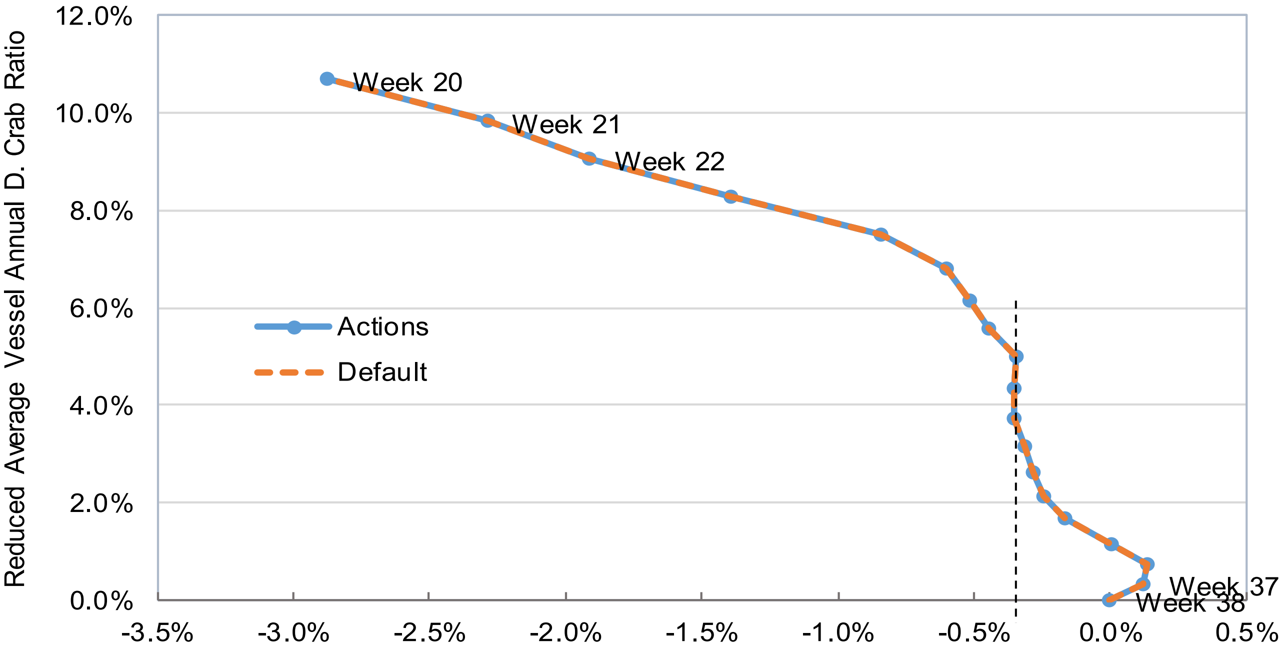


Figure XI.5 (cont.)

3. Economic impacts



4. Opportunity



Notes:
1. Each dot represents early closure week from Week 20 to 38. The dashed vertical lines show season timing for an eight-week early closure.
2. The analysis did not include modifications to model assumptions, therefore the management action alternative's trajectory is superimposed on the default assumptions trajectory.
3. The *y*-axis percents are actions minus status quo divided by status quo.
4. The base period annual average fishing mortality is 17.0 million pounds (280 thousand pounds handling, 56 thousand pounds cannibalism, and 16.7 million pounds retained catch). The base period annual average net revenue is $22.3 million.

Table XI.1
Season Biomass and Mortality Accounting for Base Period With
an Eight-Week Early Closure Management Action

	Base Period	Difference	Results	Percent Difference
Beginning biomass			174,381,912	
Existing			34,048,579	
Recruitment			140,333,333	
Handling mortality	335,837	-230,884	104,954	-68.7%
Sublegal soft	21,500	---	0	-100.0%
Sublegal hard	109,078	-8,024	101,054	-7.4%
Legal soft	142,916	---	0	-100.0%
Legal hard	6,441	-2,542	3,899	-39.5%
Cannibalism/predation	55,902	---	0	-100.0%
Retained catch	16,696,522	-32,011	16,664,511	-0.2%
Natural mortality				
In season			92,812,661	
After season			16,298,387	
Total fishing and natural			125,880,513	
Ending biomass			38,525,609	
Discards	19,668,743	-3,055,663	16,613,080	-15.5%

Notes:
1. Table values are pounds.
2. Difference includes current and following seasons. Biomass and natural mortality are for current season.
3. A dash in the difference column means the calculation approximates the base period amount.
4. Discards are either gender, any size, and any condition (live or dead). They are total removals minus retained catch. Handling mortality is that portion of discards that are male and sublegal/legal size. They are either dead on deck or will have a delayed death once discarded.

Table XI.2
Season Economic Impacts for an Eight-Week Early Closure Management Action

	Base Period	Difference	Results	Percent Difference
Harvester				
Pounds	16,696,522	-32,011	16,664,511	-0.2%
Revenue	43,904,894	-214,196	43,690,699	-0.5%
Profitability	22,251,421	-78,822	22,172,600	-0.4%
Processor				
Wholesale value	68,861,645	-262,044	68,599,601	-0.4%
Communities				
Income	70,705,888	-301,382	70,404,506	-0.4%
Processor	14,711,306	-28,205	14,683,100	-0.2%
Harvester	55,994,582	-273,177	55,721,405	-0.5%
Total job equivalents	1,768	-8	1,760	-0.4%

Notes:
1. Difference includes current and following seasons.
2. Total job equivalents are average full and part-time jobs based on annual average net earnings, and assume average income per job of $40,000. Statewide and coastwide average earnings for 2013 were $45,783 and $34,137, respectively.
3. Income includes "multiplier effect" at the state level.

(this page is intentionally left blank)

XII. FUTURE RESEARCH

The bioeconomic model was designed for analyzing certain management policies. However, enhancements would be necessary for analyzing a wider set of management options. Examples are:

- Heppell and Thompson (2010) raise the possibility of harvesting females which would "not lead to sex ratios that would compromise productivity."
- Other crab fisheries, such as the Chesapeake Bay blue crab fishery, have markets for soft-shell crab.
- Several crustacean fisheries including the Alaskan crab fisheries and the New Zealand spiny rock lobster fishery employ stock assessments and individual and tradeable quota based management. Management of the Florida spiny lobster fishery uses an individual pot trading program.
- The U.S. northeast American lobster fishery has slot limits to maximize seeding and conserve large crab fecundity.
- The State of Washington has a Dungeness crab fishery based on even flow management structure with fair start provisions.
- The southeast Alaska Dungeness crab fishery has an interval closure to assist in avoiding local depletions and unsustainable harvest levels.[1]

The analysis of all of these examples is outside the capabilities of the model.

Additional data and research will be necessary to enhance the model. Heppell and Thompson (2010) state that current information is not sufficient to evaluate population dynamics and resource sustainability. ODFW (2014) lists studies necessary for improved management of the fishery. The study categories are:

- Recruitment Studies
- Gear Studies
- Marine Debris
- Connections Between Estuary and Ocean Populations
- Climate Change
- Movement Studies
- Gear and Habitat Interactions

Given both the needs of fishery management and existing model limitations, we offer a list for potential research and model enhancements without ranking, sequencing, or scoping (tasks and budget requirements). While the basis for the suggestions arose as a result of this Oregon fishery study, list items are applicable as well to the management of Washington and California Dungeness crab fisheries. Undertaking a cooperative research program among the three states may provide a more flexible, encompassing, and cost efficient approach. There would be numerous organizational structures to implement a cooperative research program including institutes associated with universities, three-state industry associations, non-profit councils with advisory and science committees, or expanding the mission of the existing Pacific States Marine

1. Southeast Alaska crab resource abundance status as indicated by the fishery's beginning split's first seven days CPUE is compared to two threshold levels that are used to determine the second split's calendar length.

Fisheries Commission Tri-State Dungeness Crab Program. The selected organization's purpose would be to develop, prioritize, secure funding, and carry-out fishery research.[2] An added service might be to assist each state to review their management under the framework of a "management strategy evaluation" process (Punt et al. 2016, Holland and Herrera 2009).

The suggested list of potential research and model enhancements includes:

1) To continue to operate and refine the discard mortality rate sampling project with increased emphasis on science-based sampling to incorporate representative harvesting (location and depth) and timing. Ride along sampling (n=22) results used for the bioeconomic model were based on only a season coverage strategy rather than depth or fishing ground location. In addition, add additional sampling responsibilities for observers to include catch and discard length frequency and pot sensor readings (subsurface temperature, salinity, etc.). A representative observer program could also detect the onset and extent of crab moulting which could lead to additional management measures to protect soft-shell crab discard mortality similar to Washington State summer season management program.[3]

2) Design and plan a fishery independent data collection program to be used to help develop stock assessments. Since surveys are expensive there would need to be a thorough evaluation of biological, ecosystem, and economic benefits prior to implementing. The stock assessment modeling would inform management as well as bioeconomic model development. The enhanced model would allow investigations to determine how long-term yield might be affected by reductions in decreased exploitation rates.

3) Include processor product recoveries and profitability in the modeling structure. It would be necessary to obtain additional processor data about product form yields, manufacturing product form shares, and manufacturing costs.

4) Use harvester and processor expenditures to determine economic impacts. (Existing method uses FEAM derived ratio estimators that are based on harvest pounds.)

5) Relate the spatial choice of grounds to economic behavior (such as greater efficiency due to higher RPUE), safety, competition (such as pots deployed per sandy and unconsolidated bottom 60 fm depth or less), and knowledge based cooperation.

6) Add a management option for interval intra-season timing closures and/or intra-season zonal closures. Example applications would be to avoid whale migration periods or avoid presence of soft-shell crab life stages.

7) Use time variant catchability for fleet class and spatial zones. (Existing method is fleetwide and areawide.)

---

2. If the PFMC managed the Dungeness crab fishery, the inclusion of fishery research needs would be mandated by the MSA of 2006. Section 302(h)(7) requires that each council develop a five-year research priority plan.
3. Washington State summer program is shoreward of a four-mile line from July 1 through September 15. Bi-weekly monitoring during ride-along trips can trigger restrictive trip limits or season closure depending on presence threshold for soft-shell crab.

8) Apply spatial-temporal data smoothing techniques to data series information. Many modeling factors are determined from statistical (curve fitting) smoothing. Time scale analysis assumes not only correct functional relationships, but also the relationships do not change over time. Technology changes, prices, operational costs, and other stochastic shocks can invalidate the smoothing results.

9) Generate social and economic profiles of fishery participants to determine interrupted season impacts on harvester operations, processor market channels, and other effects such as displacement to other fisheries. A subset of the investigation would include participants who are vertically integrated in order to determine whether economic effects include regional retail sector operations.

10) Supplement existing information about harvester and processor cost-earnings to validate the existing profitability calculations. (Existing information adapted from FEAM annual vessel and processor pro forma income statements using key informant harvester (n=10) and processor (n=4) interviews.)

11) Adapt the model framework to allow game theory investigations based on fleet profitability for new management actions. The adaption would also assist in evaluating stochastic simulations that includes process error and estimation error.

12) There would be a need for additional scientific research to set thresholds for in-season restrictive management response. The research would be to better understand whether in-season fishing depletion or natural resource life cycle stages are the cause for decreasing CPUE. Larval dispersion and juvenile/adult migration may preclude over-exploitation consequences. There may not necessarily be long-term yield gains realized for more restrictive management. However, having a modeling management option to assess economic impacts might be useful in local harvest areas where resource depletion is a conservation concern. This would provide more immediate indicators of stock abundance than is now provided by generational trends.

13) Show net economic value (NEV) at an Oregon and national economy level. This may require a consumer willingness-to-pay (WTP) survey, and depending on availability of appropriate benefit transfer measurements, may also need a general population WTP survey to determine non-market valuations. Using NEV would allow a time scale introduction, and benefit-cost metrics could be generated. Using NEV would help evaluate whether other fisheries are (dis)advantaged due to regulatory changes including the recreational fishery.

14) Improve the underlying effort based econometric model(s) including refined development of predictor variables the fleet-class level. In addition, develop an econometric demand model so that harvest price can be calculated endogenously. The model would be especially important in predicting price effects of seasonal or quota management and impacts of delays to the season start. A side benefit would be its utility in pre-season price negotiations.

15) Include vessel and processor fixed costs to improve effort prediction. For example, it is likely that the smaller summer vessels have lower fixed costs than vessels that fish earlier in the year. Profitability absent fixed costs assumes the fleet is financially homogenous for the fixed cost accounting center.

16) Explore using in-season stock condition indicators to improve fishery management. For example, Zhang et al. (2004) suggests condition indicators may indicate excessive exploitation rates as indicated by CPUE and discards per retained crabs. Evaluate whether use of such indicators on a spatial or temporal scale can indicate localized depletions or whether it can predict long term impacts on resource productivity. Such indicators may become valuable if changing ocean conditions such as warming or acidification lead to recruitment failures.

    There would be a need for additional scientific research to set thresholds for in-season restrictive management response. The research would be to better understand whether in-season fishing depletion or natural resource life cycle stages are the cause for decreasing CPUE. Larval dispersion and juvenile/adult migration may preclude over-exploitation consequences. There may not necessarily be long-term yield gains realized for more restrictive management. However, having a modeling management option to assess economic impacts might be useful in local harvest areas where resource depletion is a conservation concern. This would provide more immediate indicators of stock abundance than is now provided by generational trends.

17) Hold a Dungeness crab science and management biennial meeting for the West Coast including Alaska and British Columbia. The meeting would be a forum to share research and management findings, ideas, and collaborative opportunities.[4]

The relatively long list of research ideas implies the importance of continued fishery research and improving the structure of the bioeconomic model. While the model provided a systematic approach for generating integrated bioeconomic information, the model should be considered a continuing "work in progress." The model should be improved and adapted as the fishery changes and new economic, environmental, ecological, and management information becomes available (Larkin et al. 2011).

4. For an example of science meetings, see proceedings from the Alaska Sea Grant College Program sponsoring of the Lowell Wakefield Fisheries Symposium series. It is an annual conference started in 1982. It is in partnership with the Alaska Department of Fish and Game, NOAA National Marine Fisheries Service, and the North Pacific Fishery Management Council.

XIII. DISCUSSION

Developing a Dungeness crab bioeconomic model provides a tool to inform decision making about the impacts of fishery management policies and practices. The model methods were not developed to necessarily advance bioeconomic modeling theory, but to provide a management-level tool for generating economic impact results. As a seasonal management model, the tool has limitations for analyzing long-term harvest effects that may extend across multiple seasons.[1] The value of using the tool is to increase the understanding of biological and economic interactions and to formulate changes in policy that can increase fishery benefits.

The following four sets of management scenarios provide examples of the usefulness of the model for analyzing alternative management actions alone or in combination with changes in other model economic and biological assumptions.

1) The main purpose for developing the model was to explore potential effects from early closure to avoid discard mortality on soft-shell crabs. Results showed there were not significant economic benefits associated with reducing the season. There would be a slight increase in overall fleet profitability for a couple of weeks early closure (0.1 percent at two weeks), then economic benefits dramatically decrease for earlier season closures. The seasonal economic impacts from an eight-week early closure are a negative $214 thousand harvest value and negative $79 thousand profitability. There are winners and losers for the management change. For example, the summer type vessel class had a decrease of $186 thousand profitability and all other vessel class increased profitability by $107 thousand for an eight-week early closure. The conservation tradeoff is a 69 percent decrease in handling mortality. The eight-week early closure economic impacts are a negative $301 thousand personal income to the State's economy. The economic impacts are from harvester and processor effects and do not address effects on retail operations for the whole cooked fresh product market during the Oregon Coast summer visitor season.

2) The model is capable of assessing economic effects due to combinations of changing environmental conditions and changing fishing intensity. For example, if the moult occurred two weeks and four weeks earlier and there is a 10 percent decrease in season effort, the change to profitability would be negative 3.8 percent and negative 5.3 percent respectively.

3) The model can be used to contrast and compare alternative management actions in addition to being able to compare a management action to the status quo. An analyst would use the gross impacts from two program runs for the comparison. A demonstration situation could be the expectations of a season opening on December 1 with a $3.00 starting ex-vessel price in the current season. The hypothetical season is delayed by four weeks due to crab meat yields being below standards and the starting price is $2.85. The results from the two program runs could be imported into an external

1. The model structure would allow making consecutive iterative program runs to approximate longer term analysis. A model enhancement would be necessary for an automatic analysis to determine long-term harvest sustainability levels and finding optimum management techniques.

program, such as a new Excel workbook, and subtracted from each other. Comparing the two cases would show that delaying the season one month and starting at lower prices would result in a harvest value decrease of $13.6 million and community economic impacts decrease of $20.3 million income.

4) Model runs demonstrated that the effects of natural mortality are magnitudes greater than the effects of handling mortality and that any savings that might be gained by soft-shell management protection would comparatively be very small. For example, the model showed that an eight-week early closure results in an increase of 231 thousand pounds in handling mortality while during the same eight-week period sublegal and legal natural mortality totaled 12.7 million pounds. These results illustrate the importance of resource scale and environmental variability. Results also illustrate the "sensitivity" of the model to various assumptions, and underscore the need for research in determining the accuracy of critical economic and biological variables given their significant effects on determining the "best" management actions.

The utility in using the modeling tool is raising awareness of economic impacts when formulating management changes. It provides a connection between biological concerns and economic objectives in the search for better management strategies. Having the economic impact information readily available supports more focused research as well as fosters heightened collaborative relationships among stakeholders for managing the fishery.

XIV. BIBLIOGRAPHY

Agar, J.J. and J.G. Sutinen. "Rebuilding Strategies for Multispecies Fisheries: A Stylized Bioeconomic Model." *Environmental and Resource Economics* 28: 1-29. 2004.

Ainsworth, Justin C., Mitch Vance, Matthew V. Hunter, and Eric Schindler. The Oregon Recreational Dungeness Crab Fishery, 2007-2011. Oregon Department of Fish and Wildlife Information Report No. 2012-04. July 2012.

Anderson, J.L., C.M. Anderson, J. Chu, J. Meredith, F. Asche, G. Sylvia, et al. "The Fishery Performance Indicators: A Management Tool for Triple Bottom Line Outcomes." PLoS ONE 10(5):e0122809.doi:10.1371/journal.pone. 0122809. 2015.

Bockstael, N.E. and J. Opaluch. "Discrete Modelling of Supply Response Under Uncertainty: The Case of the Fishery." *Journal of Environmental Economics and Management* Volume 10, pages 125-137. 1983.

Branch, T.A., R. Hilborn, A.C. Haynie, G. Fay, L. Flynn, J. Griffiths, K.N. Marshall, J.K. Randall, J.M. Scheurell, E.J. Ward, M. Young. "Fleet Dynamics and Fishermen Behavior: Lessons for Fisheries Managers." *Canadian Journal of Fisheries and Aquatic Sciences* 63: 1647-1668. 2006.

Butler, T. "Maturity and Breeding of the Pacific Edible Crab, *Cancer Magister*." *Dana. J. Fish. Res. Board Can.* 17, 641–646. 1960.

Byrne, Maria and Rachel Przeslawski. "Multistressor Impacts of Warming and Acidification of the Ocean on Marine Invertebrates' Life Histories." *Oxford Journals* Volume 53, Issue 4, pg. 582-596. 2013.

Chudnow, Rachel. In Search of Effective Management: Case Study of the British Columbia Dungeness Crab *(Cancer Magister)* Fishery and Lessons from Domestic and International Experience. MS Thesis, University of British Columbia (Vancouver). December 2012.

Clark, Colin W. "Towards a Predictive Model for the Economic Regulation of Commercial Fisheries." *Canadian Journal of Fisheries and Aquatic Sciences* 37 (7): 1111–29. 1980.

Cleaver, F.C. Preliminary Results of the Coastal Crab *(Cancer Magister)* Investigation. State of Washington, Department of Fisheries. 1949.

Demory, D. "An Overview of Oregon Dungeness Crab Fishery With Management Concepts for the Future." *In* Proceedings of the symposium on Dungeness crab biology and management. University of Alaska Fairbanks, Alaska Sea Grant Report 85-3. pp. 27–32. 1985.

Dewees, Christopher M., Kristen Sortais, Matthew J. Krachey, Steven C. Hackett, and David G. Hankin. Racing for Crabs . . . Costs and Management Options Evaluated in Dungeness Crab Fishery. California Agriculture: Vol. 58: No. 4, Page 186. 2004.

Diamond, Nancy and David G. Hankin. "Movements of Adult Female Dungeness Crabs *(Cancer Magister)* in Northern California Based on Tag Recoveries." *Canadian Journal of Fisheries and Aquatic Sciences* 42(5):919-926. April 2011.

Didier, A.J. <u>The Pacific Coast Dungeness Crab Fishery</u>. Pacific States Marine Fisheries Commission. 2002.

Dunham, J.S., Phillips, A., Morrison, J., and Jorgensen, G. "A Manual for Dungeness Crab Surveys in British Columbia." *Canadian Technical Report of Fisheries and Aquatic Sciences* 2964. 2011.

Ferraris, Jocelyne. <u>Fishing Fleet Profiling Methodology</u>. FAO Fisheries Technical Paper 423. 2002.

Fishery Economic Assessment Model (FEAM) maintained for ODFW. The Research Group, LLC (TRG). <u>Oregon's Commercial Fishing Industry, Year 2013 and 2014 Review</u>. Prepared for Oregon Department of Fish and Wildlife, and Oregon Coastal Zone Management Association. September 2015.

Gordon, H.S. "The Economic Theory of a Common-Property Resource: The Fishery." *The Journal of Political Economy* Vol. 62, No. 2. 1954.

Gotshall, D.W. "Northern California Dungeness Crab, *Cancer Magister,* Movements as Shown by Tagging." California Fish and Game 64(4): 234–254. 1978.

Gutermuth, F. "Temperature-Dependent Metabolic Response of Juvenile Dungeness Crab *Cancer Magister."* Dana: ecological implications for estuarine and coastal populations. *J. Exp. Mar. Biol. Ecol.* 126, 135–144. 1989.

Halpern, Benjamin S., Carissa J. Klein, Christopher J. Brown, Maria Beger, Hedley S. Grantham, Sangeeta Mangubhai, Mary Ruckelshaus, Vivitskaia J. Tulloch, Matt Watts, Crow White, and Hugh P. Possingham. "Achieving the Triple Bottom Line in the Face of Inherent Trade-Offs Among Social Equity, Economic Return, and Conservation." Proceedings of the National Academy of Sciences of the United States of America (PNAS), vol. 110, no. 15, pgs. 6229–6234. April 2013.

Hankin, David G., Steven C. Hackett, and Christopher M. Dewees. <u>California's Dungeness Crab: Conserving the Resource and Increasing the Net Economic Value of the Fishery</u>. California Sea Grant College Program Research Completion Reports (University of California, San Diego) Fisheries Paper 04-05. 2005.

Hankin, D.G., Diamond, N., Mohr, M.S., and Ianelli, J. "Growth and Reproductive Dynamics of Adult Female Dungeness Crabs *(Cancer Magister)* in Northern California." *J. Cons. ICES J. Mar. Sci.* 46(1): 94–108. doi: 10.1093/icesjms/46.1.94. 1989.

Hankin, D.G., N. Diamond, M.S. Mohr, and J. Ianelli. "Molt Increments, Annual Molting Probabilities, Fecundity and Survival Rates of Adult Female Dungeness Crab in Northern California." Proceedings of the Symposium on Dungeness Crab Biology and

Management, pgs 189-206. University of Alaska Fairbanks, Alaska Sea Grant College Program, AK-SG-85-03. 1985.

Heppell, Selina S. and Kevin Thompson. Development of Monitoring and Assessment Tools for the Dungeness Crab Fishery. Report to the Oregon Dungeness Crab Commission, Coos Bay, Oregon. 2010.

Higgins, K., Hastings, A., Sarvela, J.N., and Botsford, L.W. "Stochastic Dynamics and Deterministic Skeletons: Population Behavior of Dungeness Crab." *Science* 276: 1431–1435. 1997.

Hobbs, R.C., Botsford, L.W., and Thomas, A. "Influence of Hydrographic Conditions and Wind Forcing on the Distribution and Abundance of Dungeness Crab, *Cancer Magister,* Larvae." *Can. J. Fish. Aquat. Sci.* 49(7): 1379–1388. 1992.

Holland, Daniel S. and Guillermo (Ta) E. Herrera. "Uncertainty in the Management of Fisheries: Contradictory Implications and a New Approach." *Marine Resource Economics,* Volume 24, pp. 289-299. 2009.

Ives, M., J. Scandol, and J. Greenville. "A Bio-economic Management Strategy Evaluation for a Multi-species, Multi-fleet Fishery Facing a World of Uncertainty." *In* Ecological Modeling. 2013.

Jacobson, Kaety. Adult Male Dungeness Crab *(Metacarcinus Magister)* Movements Near Reedsport, Oregon; A Collaborative Mark-Recapture Study. 2016.

Jacobson, Kaety. Adult Male Dungeness Crab *(Metacarcinus Magister)* Movements Near Reedsport, Oregon; A Collaborative Mark-Recapture Study. 2011.

Jensen, G.C. Pacific Coast Crab and Shrimps. Sea Challengers, Monterey, California. 1995.

Jensen, G.C. and Armstrong, D.A. "Range Extensions of Some Northeastern Pacific Decapoda." *Crustaceana* 52(2): 215–217. 1987.

Johnson, D.F., Botsford, L.W., Methot Jr., R.D., and Wainwright, T.C. "Wind Stress and Cycles in Dungeness Crab *(Cancer Magister)* Catch Off California, Oregon, and Washington." *Can. J. Fish. Aquat. Sci.* 43(4): 838–845. 1986.

Jow, T. California-Oregon Cooperative Crab Tagging Study. Pacific Marine Fisheries Commission 16th and 17th annual report for the year 1964, pgs. 51- 52. 1965.

Jow, T. "California-Oregon Cooperative Crab Tagging Study." *Pac. Mar. Fish. Comm.* 16-Th 17-Th Annu. Rep. Year 1964 64: 51–52. 1963.

Larkin, Sherry, Sergio Alvarez, Gil Sylvia, and Michael Harte. "Practical Considerations in Using Bioeconomic Modelling for Rebuilding Fisheries." *In* OECD Food, Agriculture and Fisheries Working Paper No. 38. 2011.

Larkin, S. and G. Sylvia. "Generating Enhanced Fishery Rents by Internalizing Product Quality Characteristics." *Environmental and Resource Economics,* 28 (1):101-122. 2004.

MacKay, D.C.G. The Pacific Edible Crab, *Cancer Magister*. Fisheries Research Board of Canada. Bulletin 62. 1942.

McCabe, George T., Robert L. Emmett, Travis C. Coley, and Robert J. McConnell. Distribution Abundance, and Size-class Structure of Dungeness Crabs in the Columbia River Estuary, a River-Dominated Estuary. Coastal Zone and Estuarine Studies Division, Northwest and Alaska Fisheries Center, National Marine Fisheries Service. January 1987.

Methot Jr., R.D., and Botsford, L.W. "Estimated Preseason Abundance in the California Dungeness Crab *(Cancer Magister)* Fisheries." *Can. J. Fish. Aquat. Sci.* 39(8): 1077–1083. 1982.

Miller, J.J., M. Maher, E. Bohaboy, et al. "Exposure to Low pH Reduces Survival and Delays Development in Early Life Stages of Dungeness Crab." *Marine Biology* 163:118. 2016.

National Marine Fisheries Service (NMFS). Fisheries of the United States 2014. Office of Science and Technology Current Fishery Statistics No. 2014. September 2015.

Northwest Fisheries Science Center (NWFSC). Personal communication concerning IOPAC surveys with Jerry Leonard. March 2016.

Oh, S.J. and Hankin, D.G. "The Sperm Plug is a Reliable Indicator of Mating Success in Female Dungeness Crabs, *Cancer Magister*." *J. Crustac. Biol.* 24(2): 314–326. doi: 10.1651/C-2389. 2004.

Oregon Department of Fish and Wildlife (ODFW). Personal communication with Kelly Corbett. December 2016.

Oregon Department of Fish and Wildlife, Marine Resources Program (ODFW). Oregon Dungeness Crab Research and Monitoring Plan. Updated August 2014.

Oregon Department of Fish and Wildlife (ODFW). Oregon Commercial Dungeness Crab Summer Fishery Management. Prepared by Neal Coenen and Rod Kaiser for the Oregon Fish and Wildlife Commission. October 1999.

Organization for Economic Cooperation and Development (OECD). Toward Sustainable Fisheries: Economic Aspects of the Management of Living Marine Resources. Organization for Economic Cooperation and Development, Paris. 1997.

Pascoe, S., D. Greboval, and J. Kirkley. "A Framework for Capacity Appraisal in Fisheries." *In* D. Grebova (ed.) Measuring and Appraising Capacity in Fisheries: Framework, Analytical Tools, and Data Aggregation. FAO Fisheries Circular No. 994, Rome. 2004.

Pew Charitable Trusts (Pew). Management Strategy Evaluation for Fisheries: Informing the Selection of Harvest Strategies. Fact Sheet. Via Internet: http://www.pewtrusts.org/~/media/assets/2016/11/managementstrategyevaluation_web.pdf. January 2016.

Prellezo, Raúl, Paolo Accadia, Jesper L. Andersen, Bo S. Andersen, Erik Buisman, Alyson Little, J. Rasmus Nielsen, Jan Jaap Poos, Jeff Powell, and Christine Röckmann. "A Review of EU Bio-Economic Models for Fisheries: The Value of a Diversity of Models." Marine Policy 36 (2): 423–31. 2012.

Punt, Andre, Doug S. Butterworth, Carryn L. de Moor, José A.A. De Oliveira, and Malcolm Haddon. "Management Strategy Evaluation: Best Practices." *Fish and Fisheries* Volume 17, Issue 2. June 2016.

Rasmuson, L.K. "The Biology, Ecology and Fishery of the Dungeness Crab, *Cancer Magister*." *In* Advances in Marine Biology. Elsevier. pp. 95–148. Available from http://linkinghub.elsevier.com/retrieve/pii/ B9780124104983000033 [accessed 9 April 2015]. 2013.

The Research Group, LLC (TRG). Oregon's Commercial Fishing Industry, Year 2013 and 2014 Review. Prepared for Oregon Department of Fish and Wildlife, and Oregon Coastal Zone Management Association. September 2015.

Robinson, J.G., Odemar, M.W., Richards, J.A., and Westley, R. Report on the Proposal for Extension of Dungeness crab State/Federal Fisheries Management Plan Development for the California, Oregon, and Washington Dungeness Crab Fishery. Available from https://ir.library.oregonstate.edu/xmlui/bitstream/handle/ 1957/25581/ReportProposalExtensionDungeness.pdf?sequence=1 [accessed 15 April 2015]. 1977.

Schaefer, M.B. "Some Aspects of the Dynamics of Populations Important to the Management of Commercial Marine Fisheries." Inter-American Tropical Tuna Commission Bulletin Vol. 1 No. 2. 1954.

Shanks, Alan L. and G. Curtis Roegner. "Recruitment Limitation in Dungeness Crab Populations is Driven by Variation in Atmospheric Forcing." *Ecology* 88 (7), 1726-1737. 2007.

Shanks, A., Roegner, G., and J. Miller. "Using Megalopae Abundance to Predict Future Commercial Catches of Dungeness Crab *(Cancer Magister)* in Oregon." CalCOFI Rep. 51: 1-13. 2010.

Shirley, T.C. and M. Sturdevant. Dungeness Crab Mating Study. University of Alaska Southeast, School of Fisheries and Science, Annual Report to the Alaska Department of Fish and Game UASE 87-20, Juneau. 1988.

Smith, B.D. and Jamieson, G.S. "Exploitation and Mortality of Male Dungeness Crabs *(Cancer Magister)* Near Tofino, British Colombia." *Can. J. Fish. Aquat. Sci.* 46(9): 1609–1614. 1989.

Somers, K.A., M. Bellman, J. Jannot, N. Riley, and J. McVeigh. Estimated Discard and Catch of Groundfish Species in the 2013 U.S. West Coast Fisheries. NOAA Fisheries, NWFSC Observer Program, 2725 Montlake Blvd E., Seattle, WA 98112. October 2014.

Sylvia, G. and R. Enriquez. "Multiobjective Bioeconomic Analysis: An Application to the Pacific Whiting Fishery." *Marine Resource Economics,* 9(4):311-328. 1995.

Tegelberg, H.C. "Condition, Yield, and Handling Mortality Studies on Dungeness Crabs During the 1969 and 1970 Seasons." In 23rd Annual Report of the Pacific Marine Fisheries Commission for the year 1970. Portland, Oregon. pp. 42–47. Available from http://www.psmfc.org/resources/publications-maps-2/psmfc-annual-report. 1972.

Terry, Joe, Gilbert Sylvia, Dale Squires, Wes Silverthorne, James Seger, Gordon Munro, Richard Marasco, Douglas Larson, James Kirkley, Larry Jacobson, Samuel Herrick, John Gauvin, Amy Buss Gautam, Steven Freese, and Rebecca Baldwin. <u>Fixed Costs and Joint Cost Allocation in the Management of Pacific Whiting - A Workshop Report</u>. NOAA-TM-NM F S-S W FSC-234. September 1996.

Thunberg, Eric M. and Steven J. Correia. "Measures of Fishing Fleet Diversity in the New England Groundfish Fishery." Marine Policy, Volume 58. Via Internet: http://www.sciencedirect.com/science/article/pii/S0308597X15000871. August 2015.

Van Putten, Ingrid, Soile Kulmala, Olivier Thébaud, Natalie Dowling, Katell Hamon, Trevor Hutton, and Sean Pascoe. "Theories and Behavioural Drivers Underlying Fleet Dynamics Models." *Fish and Fisheries* Volume 13, Issue 2. June 2012.

Wainwright, T.C. and D.A. Armstrong. "Growth Patterns in the Dungeness Crab *(Cancer Magister)* Synthesis of Data and Comparison of Models." *Journal of Crustacean Biology* 13:36–50. 1993.

Wilberg, Michael J., James T. Thorson, Brian C. Linton, and Jim Berkson. "Incorporating Time-Varying Catchability into Population Dynamic Stock Assessment Model." Reviews in Fisheries Science, 18(1):7-24. 2010.

Windsland, Kristin. "Total and Natural Mortality of Red King Crab *(Paralithodes Camtschaticus)* in Norwegian Waters: Catch–curve Analysis and Indirect Estimation Methods." *ICES Journal of Marine Science* 72 (2): 642-650. 2014.

Yochum, Noëlle, W. Allan Stoner, David B. Sampson, Craig Rose, Alan Pazar, and Robert Eder. "Utilizing Reflex Impairment to Assess the Role of Discard Mortality in 'Size, Sex, and Season' Management for Oregon Dungeness Crab *(Cancer Magister)* Fisheries." *Canadian Journal of Fisheries and Aquatic Sciences.* 2017.

Yochum, Noëlle. Personal communication. 2016.

Yonis, Ramzi. <u>The Economics of British Columbia's Crab Fishery: Socio-Economic Profile, Viability, and Market Trends</u>. Statistical and Economic Analysis Series. Publication. No.1-4 iv + 20 p. 2010.

Zhang, Z., W. Hajas, A. Phillips, and J.A. Boutillier. "Use of Length-Based Models to Estimate Biological Parameters and Conduct Yield Analyses for Male Dungeness Crab *(Cancer Magister)." Canadian Journal of Fisheries and Aquatic Sciences* 61 (11): 2126–34. doi:10.1139/f04-155. 2004.

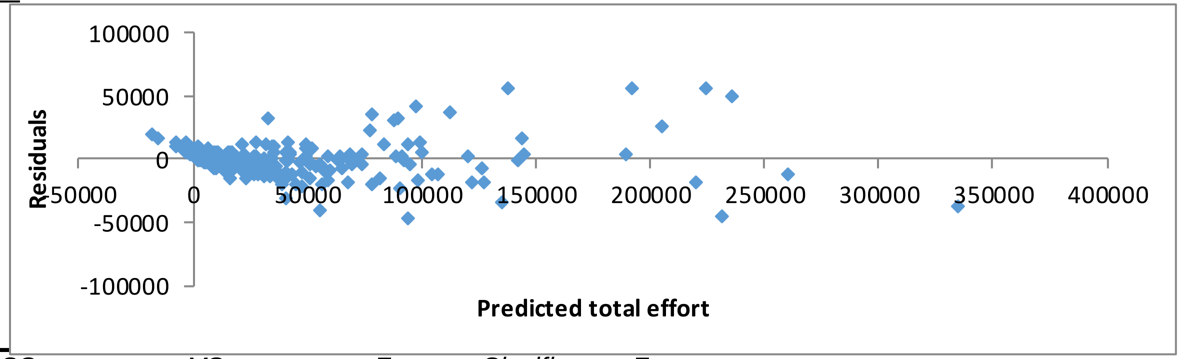
Appendix A

Effort Predictor and Retrospective Analysis

(this page is intentionally left blank)

Appendix A: Effort Predictor and Retrospective Analysis

SUMMARY OUTPUT



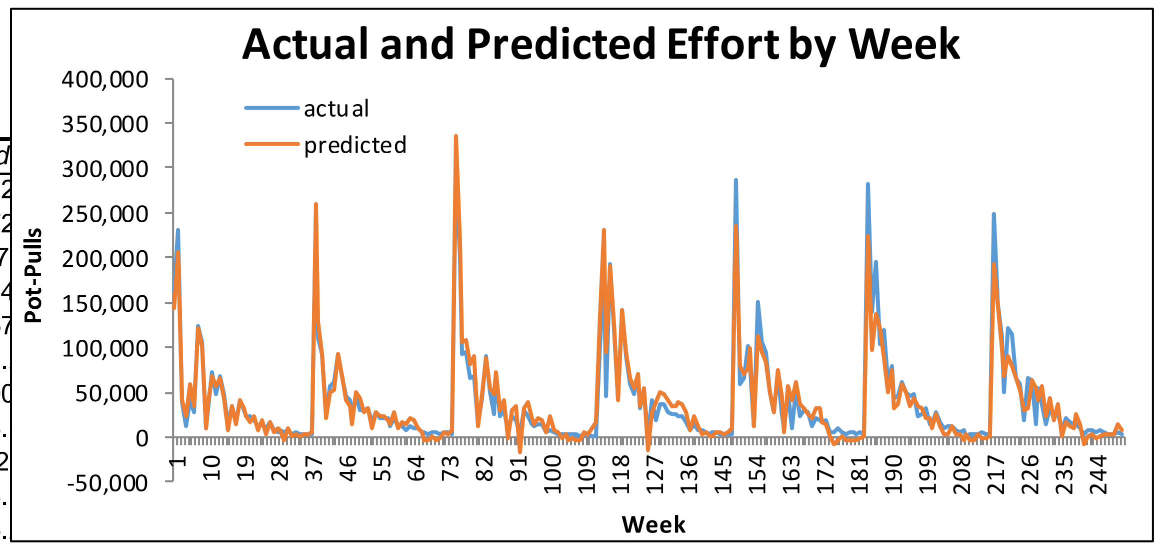
Regression Statistics	
Multiple R	0.966582826
R Square	0.93428236
Adjusted R Square	0.932941183
Standard Error	13706.59389
Observations	251

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	6.54367E+11	1.30873E+11	696.6141126	1.3719E-142
Residual	245	46028325461	187870716.2		
Total	250	7.00395E+11			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-49845.84267	14223.74862	-3.504409703	0.000543936	-77862.27386	-21829.4115	-77862.27386	-21829.41149
annual D. crab / annual all OR fis	10477.01691	17602.92403	0.595186169	0.552268372	-24195.35553	45149.38935	-24195.35553	45149.38935
week no. ^1.5	98.24016796	25.96387085	3.783725799	0.000194274	47.0992894	149.3810465	47.0992894	149.3810465
vessels	347.5867172	24.07756746	14.43612266	1.34069E-34	300.1612789	395.0121554	300.1612789	395.0121554
riskiness (var of effort by vessels)	0.49153747	0.021030291	23.37283266	2.59034E-64	0.450114234	0.532960706	0.450114234	0.532960706
RPUE(-1) (prev. week nominal re	664.3786468	117.7733391	5.641163372	4.64682E-08	432.4012168	896.3560768	432.4012168	896.3560768

RESIDUAL OUTPUT



Observation	*edicted total eff*	*Resid*
1	143744.0227	16722
2	205096.7623	26172
3	40379.04495	-643.7
4	22312.2776	-9924
5	58982.83188	-17057
6	35301.8434	-6831.
7	120665.8055	200
8	100521.3823	5463.
9	10676.74798	-528.2
10	35845.67807	-5654.
11	68512.83003	3706.
12	56931.34852	-9437.230871

Appendix A: Effort Predictor and Retrospective Analysis (cont.)

Predictor Variable Correlation Matrix

	annual D. crab / annual all OR fisheries revenue	*week no. ^1.5*	*vessels*	*riskiness (var of effort by vessels)*	*RPUE(-1) (prev. week nominal revenue-per-unit-effort)*
annual D. crab / annual all OR fisheries revenue	1				
week no. ^1.5	0.829	1			
vessels	-0.833	-0.822	1		
riskiness (var of effort by vessels)	-0.538	-0.510	0.601	1	
RPUE(-1) (prev. week nominal revenue-per-unit-effort)	-0.647	-0.567	0.598	0.704	1

Appendix A: Effort Predictor and Retrospective Analysis (cont.)

	Base Period				Status Quo				Percent Difference			
Week	Catch (pounds)	Ex-Vessel Revenue	Effort	Net Revenue	Catch (pounds)	Ex-Vessel Revenue	Effort	Net Revenue	Catch (pounds)	Ex-Vessel Revenue	Effort	Net Revenue
1	4,383,165	9,791,590	217,581	5,438,276	5,778,753	12,682,704	202,120	7,437,553	31.8%	29.5%	-7.1%	36.8%
2	3,049,267	6,661,227	141,342	3,709,387	2,774,763	6,142,231	145,135	3,341,397	-9.0%	-7.8%	2.7%	-9.9%
3	2,160,610	4,983,944	112,060	2,726,639	1,857,762	4,365,320	111,668	2,315,826	-14.0%	-12.4%	-0.3%	-15.1%
4	1,006,058	2,636,336	61,957	1,441,668	922,357	2,518,717	74,280	1,296,452	-8.3%	-4.5%	19.9%	-10.1%
5	1,134,060	3,119,476	97,003	1,562,116	1,151,995	3,275,398	94,537	1,680,334	1.6%	5.0%	-2.5%	7.6%
6	810,135	2,138,445	66,126	1,043,749	567,681	1,651,786	64,356	728,500	-29.9%	-22.8%	-2.7%	-30.2%
7	706,418	2,210,184	80,824	1,036,719	624,413	1,897,262	74,871	858,754	-11.6%	-14.2%	-7.4%	-17.2%
8	651,617	1,937,292	80,757	857,204	541,555	1,682,302	77,282	703,761	-16.9%	-13.2%	-4.3%	-17.9%
9	436,941	1,275,813	56,766	542,662	366,826	1,175,739	56,004	479,336	-16.0%	-7.8%	-1.3%	-11.7%
10	336,040	1,052,716	50,948	431,156	275,886	922,505	48,691	354,915	-17.9%	-12.4%	-4.4%	-17.7%
11	297,648	1,041,107	43,773	465,377	236,593	833,807	47,529	302,135	-20.5%	-19.9%	8.6%	-35.1%
12	252,295	839,759	52,116	289,165	255,721	926,155	60,190	303,828	1.4%	10.3%	15.5%	5.1%
13	189,347	718,263	39,902	284,089	187,256	714,677	44,147	258,777	-1.1%	-0.5%	10.6%	-8.9%
14	162,205	627,641	32,803	271,376	148,997	598,452	38,556	222,470	-8.1%	-4.7%	17.5%	-18.0%
15	93,299	404,129	20,695	173,278	97,798	418,426	19,884	187,147	4.8%	3.5%	-3.9%	8.0%
16	88,584	384,739	27,200	130,734	117,486	493,518	30,884	187,676	32.6%	28.3%	13.5%	43.6%
17	122,674	536,062	23,996	255,226	115,311	510,960	31,805	198,675	-6.0%	-4.7%	32.5%	-22.2%
18	94,487	427,550	23,434	190,460	84,708	387,546	26,751	146,239	-10.3%	-9.4%	14.2%	-23.2%
19	86,539	394,460	26,283	151,333	90,416	429,899	28,305	166,534	4.5%	9.0%	7.7%	10.0%
20	86,927	415,318	22,991	191,760	79,941	388,028	26,067	158,108	-8.0%	-6.6%	13.4%	-17.5%
21	64,804	313,215	16,120	148,459	55,340	269,172	18,547	105,414	-14.6%	-14.1%	15.1%	-29.0%
22	74,034	361,640	18,092	175,039	67,782	332,725	21,486	138,139	-8.4%	-8.0%	18.8%	-21.1%
23	52,098	250,008	15,053	114,332	69,746	334,576	22,059	144,543	33.9%	33.8%	46.5%	26.4%
24	55,499	247,409	13,840	110,360	53,288	235,489	19,079	76,204	-4.0%	-4.8%	37.9%	-30.9%
25	34,407	144,044	9,628	62,050	25,113	104,505	10,031	31,644	-27.0%	-27.4%	4.2%	-49.0%
26	34,886	146,031	9,341	63,808	27,867	114,157	10,441	35,541	-20.1%	-21.8%	11.8%	-44.3%
27	31,804	133,239	7,446	65,358	26,263	104,659	8,642	39,161	-17.4%	-21.5%	16.1%	-40.1%
28	25,355	93,013	6,339	41,944	10,358	38,010	4,861	7,519	-59.1%	-59.1%	-23.3%	-82.1%
29	22,664	80,477	5,957	32,692	7,240	25,508	3,068	5,054	-68.1%	-68.3%	-48.5%	-84.5%
30	17,682	62,382	4,571	24,489	7,176	24,823	1,373	11,863	-59.4%	-60.2%	-70.0%	-51.6%
31	17,656	62,830	4,587	25,708	6,695	23,573	1,598	10,207	-62.1%	-62.5%	-65.2%	-60.3%
32	17,666	63,397	3,609	28,958	6,771	23,761	1,144	11,899	-61.7%	-62.5%	-68.3%	-58.9%
33	17,665	64,190	3,851	28,528	10,817	38,840	1,733	20,213	-38.8%	-39.5%	-55.0%	-29.1%
34	16,210	57,045	3,564	24,076	23,649	82,059	3,323	43,826	45.9%	43.9%	-6.7%	82.0%
35	18,349	65,125	3,630	28,569	31,388	110,148	5,498	51,820	71.1%	69.1%	51.5%	81.4%
36	22,019	76,235	3,560	37,183	21,798	75,295	5,045	28,499	-1.0%	-1.2%	41.7%	-23.4%
37	25,409	88,563	3,054	47,495	44,591	154,017	9,150	59,993	75.5%	73.9%	199.6%	26.3%
Total	16,696,522	43,904,894	1,410,800	22,251,421	16,772,101	44,106,748	1,450,138	22,149,954	0.5%	0.5%	2.8%	-0.5%

(this page is intentionally left blank)

Appendix B

Recruitment and Catchability Estimator

(this page is intentionally left blank)

Appendix B: Recruitment and Catchability Estimator

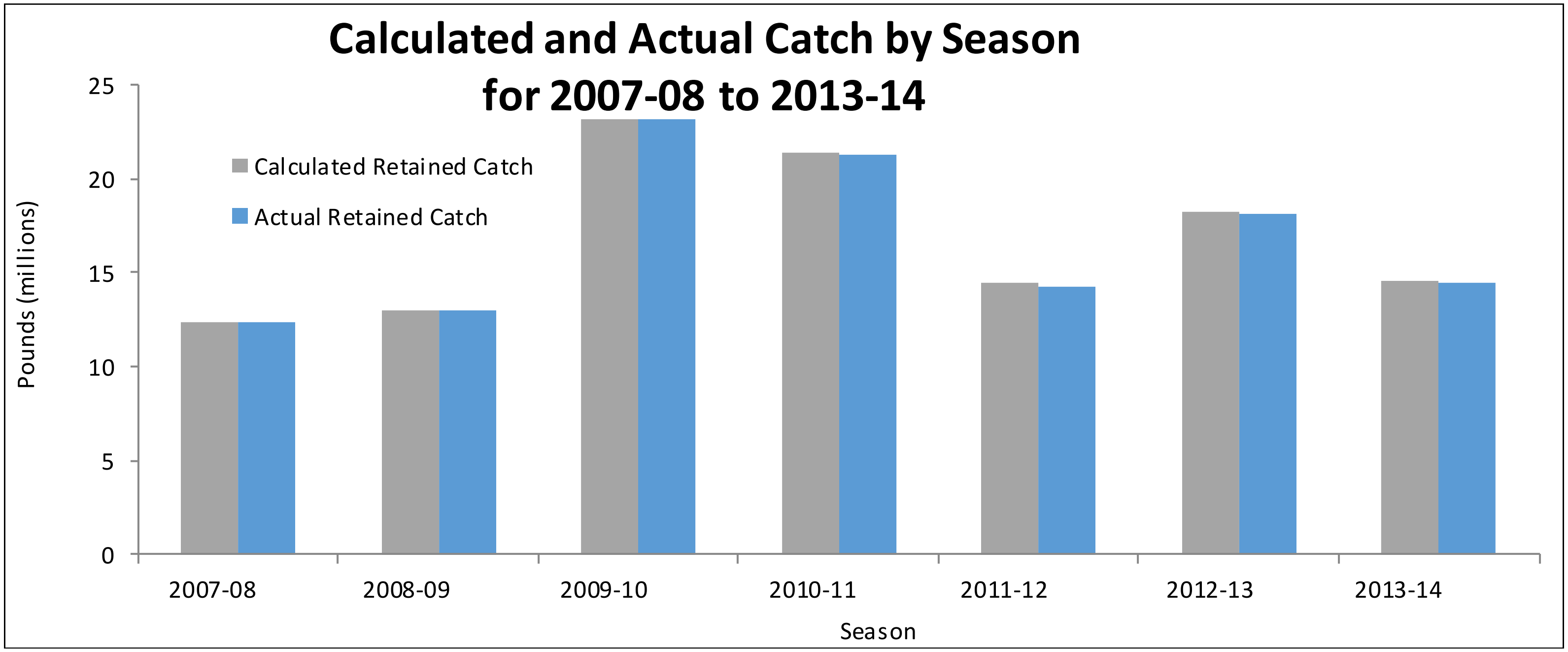
Project: ODCC Dungeness Crab Bioeconomic Model
Statement: Simulation of biomass given assumptions for pre-recruitment, natural mortality, and fishing mortality (i.e. retained catch, handling, cannibalism/predation).
Date: November 9, 2016

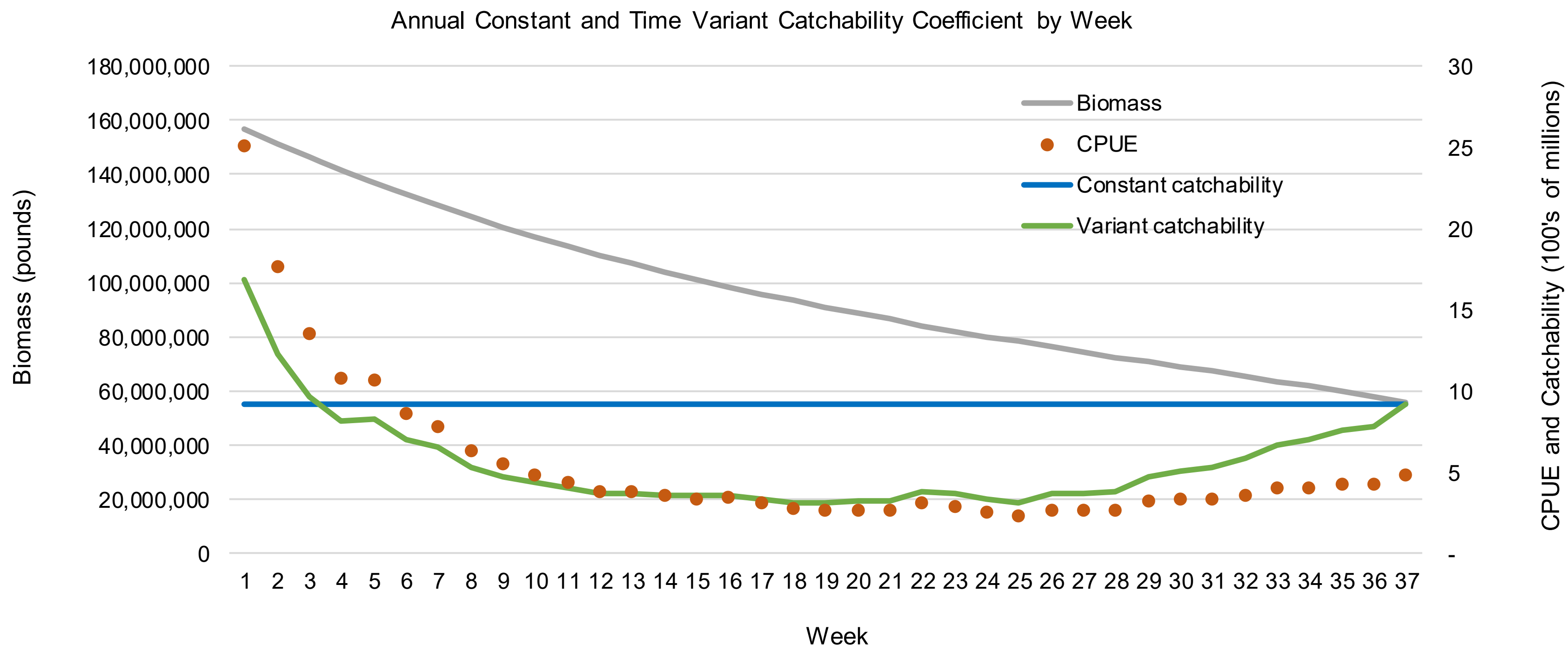
Assumptions

Initial year biomass:	120,000,000	pounds				
Initial annual recruitment:	112,500,000	pounds		annual recruitment change:	0%	
Annual natural mortality:	1.25	rate	28.71%	factor (exp(-rate))	97.63%	weekly factor (exp(-rate / 52))
Cannibalism/predation:	34.0%	of soft cohorts handling mortality (6.8% * factor)			factor:	5
Average pounds/crab:	1.17					

Season	Biomass Beginning Balance	Pre-recruitment	Catchability	Calculated Retained Catch	Calculated Handling Mortality SoftSub	HardSub	SoftLeg	HardLeg	Cannibalism/ Predation	Season Natural Mortality	Remaining Natural Mortality	Biomass Ending Balance	Actual Retained Catch
2007-08	120,000	112,500	0.00000006	12,360	18	82	120	5	47	64,034	13,101	30,233	12,337
2008-09	142,733	157,500	0.00000005	12,949	27	80	192	5	74	76,948	15,859	36,598	13,000
2009-10	194,098	97,500	0.00000005	23,179	22	130	155	6	60	101,447	20,890	48,209	23,204
2010-11	145,709	122,500	0.00000007	21,422	27	146	178	9	70	74,470	14,931	34,457	21,237
2011-12	156,957	220,000	0.00000005	14,431	1	90	2	4	1	81,829	20,302	40,297	14,284
2012-13	260,297	132,000	0.00000004	18,258	2	102	11	4	4	133,243	39,795	68,879	18,188
2013-14	200,879	132,000	0.00000005	14,552	35	100	228	8	90	106,707	26,520	52,639	14,450
Average	174,382	139,143	0.00000005	16,736	19	104	127	6	49	91,240	21,628	44,473	16,671

Notes:
1. Table values other than catchability are thousands of pounds round weight.
2. Shown table is annual compilation of a seven year, weekly table. The linear programming routines for solving catchability operate on the weekly table. Priors for initial biomass and pre-recruitment from Heppell and Thompson (2010).
3. Season beginning biomass is previous season ending biomass plus previous season recruitment. Season ending biomass is season beginning biomass minus retained catch, handling mortality, cannibalism/predation, and natural mortality.
4. Catch is calculated using the equation q * B * E by week, where B is biomass and E is a function of actual RPUE(-1) (previous week's nominal revenue per pot-pull), annual D. crab ratio to all Oregon revenue, week no., vessels, and riskiness (variance of effort by vessels).
5. The catchability rate is intra-season time variant.
6. Pre-recruitment is sublegal size for the shown year and legal size for the subsequent year.


Calculated and Actual Catch by Season
for 2007-08 to 2013-14
Calculated Retained Catch
Actual Retained Catch
Pounds (millions)
0
5
10
15
20
25
2007-08
2008-09
2009-10
2010-11
2011-12
2012-13
2013-14
Season



Notes:
1. The average is across the seven year base period.
2. Biomass is mature male sublegal and legal size crab.
3. Catch per unit effort (CPUE) is based on adjusted hailed logbook catch per pot-pull.
4. The blue line shows solved annual average constant catchability coefficient. The green line shows weekly average variant catchability coefficient.

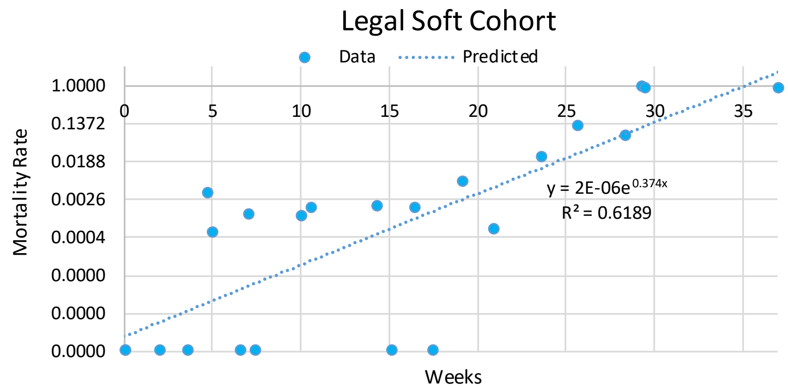
(this page is intentionally left blank)

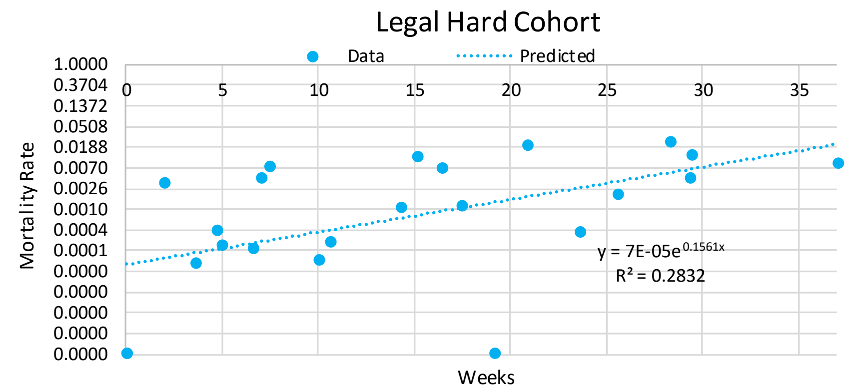
Appendix C

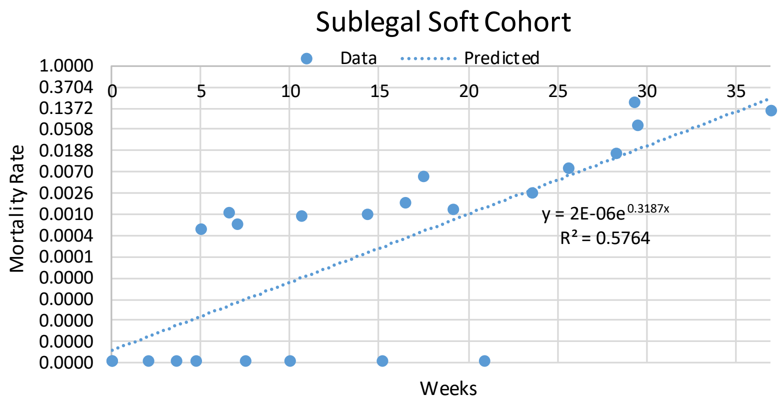
Discard and Handling Mortality Rates

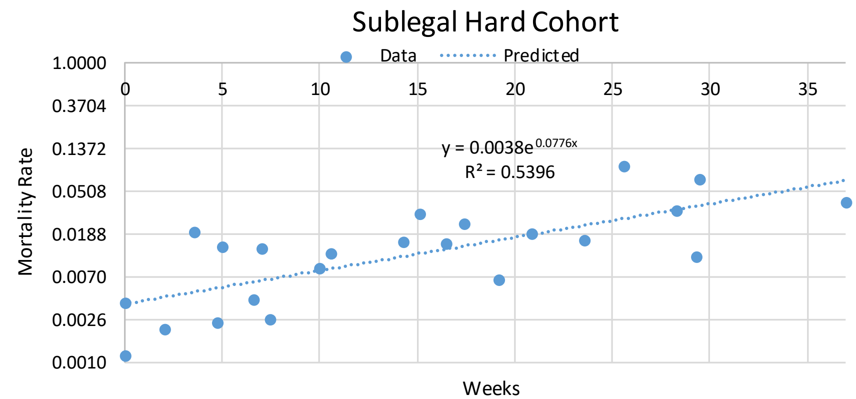
(this page is intentionally left blank)

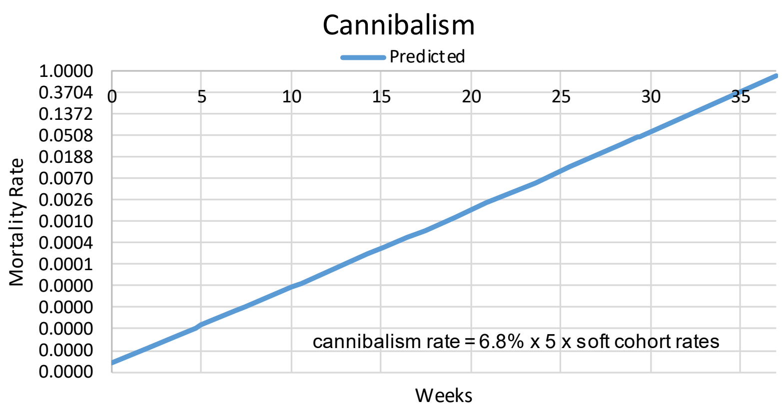
<u>Appendix C: Discard and Handling Mortality Rates</u>

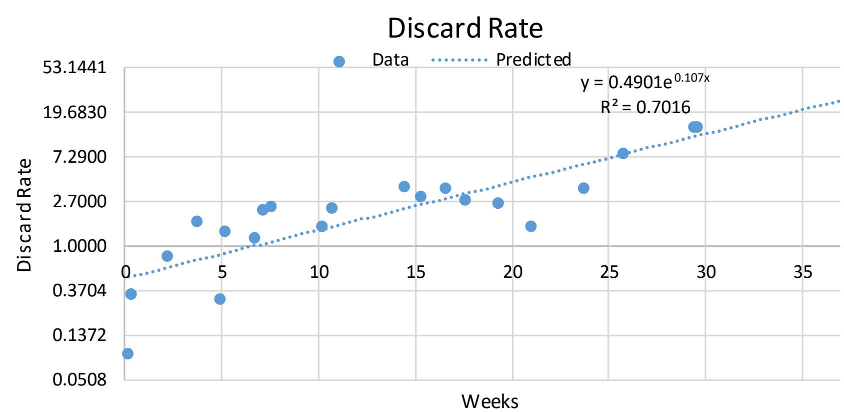












Notes:
1. The y-axes are in natural log scale.
2. Discard and mortality rates are per retained crab.
3. Cannibalism assumes the presence of soft-shell crab in the pot prior to pulling is five times the soft-shell handling mortality.
4. Discards are all genders, size, and condition (alive or dead). Handling mortality and cannibalism is mature male adults.
5. The last sampling data for discards was Week 29. Rates are predicted from the curve fit equation through the end-of-season.

Source: Yochum et al. (2017).

(this page is intentionally left blank)

Appendix D

Sensitivity Analysis

(this page is intentionally left blank)

Appendix D: Sensitivity Analysis

Assumptions	Menu	Selected Change	Results +/- Percent Difference Week 21	Week 30	Week 38
Profitability					
Biological:					
handling mortality	3.a.i.(1)	-10%	-2.2%	-0.3%	0.1%
cohort mortality week shift (one week)	3.a.i.(2)	-1 week	-2.4%	-0.5%	-0.3%
natural mortality factor per week	3.a.i.(3)	-10%	20.7%	23.0%	23.6%
catchability (current season)	3.a.ii.(1)	-10%	-12.3%	-10.7%	-10.4%
current season recruitment	3.a.i.(5)	-10%	-21.0%	-19.4%	-19.1%
Economic:					
trip variable costs by vessel classifications	3.b.i	-10%	7.6%	9.9%	10.4%
Management:					
early closure	4.c	--	-2.3%	-0.4%	0.0%
catchability week shift	3.a.ii.(2)	5	-56.6%	-53.7%	-53.3%
Revenue					
Biological:					
handling mortality	3.a.i.(1)	-10%	-3.3%	-0.4%	0.1%
cohort mortality week shift (one week)	3.a.i.(2)	-1 week	-3.4%	-0.6%	-0.3%
natural mortality factor per week	3.a.i.(3)	-10%	18.0%	21.2%	21.8%
catchability (current season)	3.a.ii.(1)	-10%	-10.4%	-7.7%	-7.3%
current season recruitment	3.a.i.(5)	-10%	-19.6%	-17.0%	-16.5%
Economic:					
trip variable costs by vessel classifications	3.b.i	-10%	-3.3%	-0.5%	0.0%
Management:					
early closure	4.c	--	-3.3%	-0.5%	0.0%
catchability week shift	3.a.ii.(2)	5	-49.1%	-45.2%	-44.7%

Notes:
1. Columns show percent difference in profitability or revenue for selected early closure weeks. Results include current and following seasons. Each row change shows results with all other dashboard settings in default positions.
2. The catchability week shift includes a delay start of five weeks. This means the catchability in a regular season Week 6 is used to calculate catch at season opening on Week 6.