RESEARCH/PD ANNUAL REPORT - FINAL REPORT

2015 annual report - final
Dan Cheney
Planning for sustainable shellfish aquaculture in complex multiple use environments: Determining social and ecological carrying capacity for south Puget Sound, Washington
R/LME/N-5
Submitted On: 05/20/2016 05:32:58 PM

METRICS & MEASURES

Metric/Measure	Value	Note
Acres of coastal habitat	0	This project is a modeling and analysis study and is not directed at habitat restoration or enhancement.
Fishermen and seafood industry personnel	0	The models developed and tested are not yet available for direct application by the seafood industry. These tools are available through the PSI modeling specialists.
Communities - economic and environmental development	0	The models developed and tested are not yet available for direct application by public agencies or private entities. These tools are available through the PSI modeling specialists.
Stakeholders - sustainable approaches	0	To be determined in followups with demonstrations of the modeling tools.
Informal education programs	0	
Stakeholders who receive information	550	Presentations were made at WAS 2016, PCSGA-NSA 2015, NSA 2015, etc.
Volunteer hours	200	Time provided by non-PSI personnel during stakeholder meetings, individual interviews, and for preparation and collection of field data. Includes WDOE time for assistance in EcoWin development, and time spent by growers and public resource managers.
P-12 students reached	0	No P-12 students were involved with this research.
P-12 educators	0	No P-12 educators participated in the project.

REQUESTED INFORMATION

Publications

Ecological Carrying Capacity for South Puget Sound, Ecopath with Ecosim
Publication Type: General Public and Advisory Reports, Fact Sheets, Posters, etc.
Publication Year: 2016
Publication Authors:
Publisher Info: Pacific Shellfish Institute, Olympia, WA
Notes:
Related URLs:

Keywords: Carrying Capacity, Ecosystem Modeling, Ecopath, Ecosim, Puget Sound, Bivalve Shellfish, Aquaculture
Publication URLs: pacshell.org
Abstract: NA
Citation: PSI. 2016. Ecological Carrying Capacity for South Puget Sound, Ecopath with Ecosim Pacific Shellfish Institute, Olympia, WA. 1 p.
Citation for Coverpage:
SG can post PDF online?: Yes
Uploaded File: EwE_1pger_Jan2016.pdf

Ecosystem Models of Species Changes in South Puget Sound from 1970 to 2012 and Simulations of Species Changes From 2012 to 2054
Publication Type: Technical Reports (non-peer-reviewed)
Publication Year: 2016
Publication Authors:
Publisher Info: Madrone Environmental Services, Duncan BC
Notes:
Related URLs:
Keywords: Carrying Capacity, Ecosystem Modeling, Ecopath, Ecosim, Puget Sound, Bivalve Shellfish, Aquaculture
Publication URLs: pacshell.org
Abstract: We used both mass balance and dynamics ecosystem models to represent historic, current and potential future ecosystem conditions in South Puget Sound. The forecast model examines the potential effects of different fisheries and aquaculture management policies on managed species in the South Puget Sound Ecosystem over the next 40 years. Our forecasts o future conditions involve simulating three potential future marine productivity regimes: - greater and more variable than that from 1970 to the present, - similar to that from 1970 to the present lower but with similar variability to that from 1970 to the present. In order to simulate likely marine production in the future we developed an Ecosim model of South Puget Sound from 1970 to the present in which we used time series of biomass, mortality and/or catches for managed shellfish, finfish, bird and marine mammal to estimate trophic dynamics and annual mean phytoplankton production. The historically estimated bottom-up and top-down dynamics were then used to initialise Ecosim forecast models from the present to 2054 driven by phytoplankton production time series reflective of the three potential marine production regimes The mass balance models of South Puget Sound in 1970 and 2012 catalogue the changes that have occurred in the biomass of several marine species of biological, cultural and economic significance. Analyses of the mass balance models suggest that the rapid expansion of shellfish aquaculture would not likely have significantly influenced the biomasses of other species. The dynamic historic model reinforces the hypothesis that shellfish aquaculture had significant room to grow between 1970 and 2012 without interfering with the energetic dynamics of wild species in South Puget Sound. Forecast models show that in all scenarios of future marine production there are few, if any, effects on the South Puget Sound ecosystem from maintaining or doubling the production shellfish aquaculture production. In a scenario in which farmed Geoduck production was increased 10 times over that of 2012 small decreases in wild bivalves were observed by 2054. Forecast modelling also suggests that current fisheries and aquaculture policies generally have the effect of allowing for rebuilding biomasses in species that had declined from 1970 to the present. Sea lions appeared to attenuate the rebuilding of biomasses of some finfish in forecasts to 2054. However scenarios modelled with mandated reduction in Sea Lion biomasses showed significant rebuilding of rockfish, salmon and gadids.
Citation: Dave Preikshot, Bobbi Hudson, and Daniel Cheney, 2016. Ecosystem Models of Species Changes in South Puget Sound from 1970 to 2012 and Simulations of Species Changes From 2012 to 2054. Prepared for the Pacific Shellfish Institute, Olympia WA. by Madrone Environmental Services, Duncan BC. 102 p.
Citation for Coverpage:
SG can post PDF online?: Yes
Uploaded File: SPS_EwE_model_07_Jan_2016.pdf

Application of the Farm Aquaculture Resource Management (FARM) model to shellfish culture in South Puget Sound

Publication Type: Technical Reports (non-peer-reviewed)
Publication Year: 2016
Publication Authors:
Publisher Info: Longline Environment Ltd
Notes: Draft Copy
Related URLs:
Keywords: Carrying Capacity, Ecosystem Modeling, FARM, EcoWin, Puget Sound, Bivalve Shellfish, Aquaculture
Publication URLs: pacshell.org
Abstract: The Farm Aquaculture Resource Management (FARM) model was applied to examine the production and ecological outcomes of different cultivation strategies at the farm scale in South Puget Sound (SPS) inlets with significant existing production, and estimate the role of shellfish farms in nutrient removal. FARM combines physical, biogeochemical, bivalve growth, and economic tools to determine shellfish production, financial performance, and local eutrophication assessment. Utilizing economic data and ecosystem services valuation methodologies assembled with previous research, FARM was adapted to estimate the economic value of nitrogen removed by shellfish at various production levels.
Citation: Joao G. Ferreira, Alhambra Cubillo, Dan Cheney, Andrew Suhrbier and Bobbi Hudson. 2016. Application of the Farm Aquaculture Resource Management (FARM) model to shellfish culture in South Puget Sound. Prepared for Pacific Shellfish Institute, Olympia, WA by Longline Environment Ltd. 13 p.
Citation for Coverpage:
SG can post PDF online?: Yes
Uploaded File: FARM_application_report_for_PESCA_final.pdf

Ecosystem goods and services of geoduck farming in South Puget Sound: A modelling analysis
Publication Type: Technical Reports (non-peer-reviewed)
Publication Year: 2015
Publication Authors:
Publisher Info: Longline Environment
Notes:
Related URLs:
Keywords: Carrying Capacity, Ecosystem Modeling, FARM, Puget Sound, Bivalve Shellfish, Geoduck Aquaculture
Publication URLs: pacshell.org
Abstract: We have simulated the ecosystem goods and services of geoduck farming in Eld Inlet Farm, property of Chelsea Farms. These results were then scaled to the whole Puget Sound basin. An individual geoduck clam (Panopea generosa) growth model was developed, based on our previously developed generic framework for bivalves (AquaShell). Geoduck growth performance was then calibrated and validated for the commercial farm. For the most part, equations were taken or adapted from the literature and parameterised for the studied site. The geoduck individual model was incorporated into the Farm Aquaculture Resource Management (FARM) model to simulate the production cycle, economics, and environmental effects of intertidal culture. Both the individual and farm-scale models are built in C++ using object-oriented programming. The FARM model was also used to classify the farm area with respect to its eutrophication status, applying the Assessment of Estuarine Trophic Status (ASSETS) model. Farm production of 17.3 t of clams per 5-year culture cycle is well reproduced by the model (14.4 t). In the area of Eld Inlet Farm, at the current culture density of 21 animals per square meter, geoduck farming provide an annual ecosystem service equivalent to 45 Population-Equivalents (PEQ, i.e. loading from humans or equivalent loading from agriculture or industry) in reducing eutrophication symptoms. This represents a potential nutrient credit trading value of over US $1,800 per year. The potential income would add 1.5% to the annual profit (US $124,900) from clam sales. A scaling exercise to the whole of Puget Sound suggests that clams provide a significant ecosystem service, of the order of 1,840 PEQ per year (about US $74,000) in removing primary symptoms of eutrophication.
Citation: Alhambra Cubillo and Joao G. Ferreira. 2015. Ecosystem goods and services of geoduck farming in South Puget Sound: A modelling analysis. Prepared for the Pacific Shellfish Institute by Longline Environment LTD. 19 p.
Citation for Coverpage:

SG can post PDF online?: Yes
Uploaded File: Final_report_geoduck_model_LLE_2015.12.22.pdf

EcoWin.NET model box division Stakeholder feedback and changes to model layout -- PESCA working document
Publication Type: Technical Reports (non-peer-reviewed)
Publication Year: 2014
Publication Authors:
Publisher Info: Longline Environment
Notes:
Related URLs:
Keywords: Carrying Capacity, Ecosystem Modeling, EcoWin, Puget Sound, Bivalve Shellfish, Aquaculture
Publication URLs: pacshell.org
Abstract: Following a review of stakeholder inputs, we propose a box layout for the EcoWin.NET ecological model of 76 boxes, with 38 boxes in the upper water column layer and 38 boxes in the lower layer. The detailed analysis, results, and their justification, are presented i the text below.
Citation: Vazquez, F., C. Saurel, and J. G. Ferreira. 2014. EcoWin.NET model box division Stakeholder feedback and changes to model layout -- PESCA working document. Prepared for the Pacific Shellfish Institute by Longline Environment Ltd. 22 p.
Citation for Coverpage:
SG can post PDF online?: Yes
Uploaded File: Stakeholders_summary_final.pdf

Ecosystem goods and services of geoduck farming in South Puget Sound: A modelling analysis
Publication Type: Presentations (non-peer-reviewed)
Publication Year: 2015
Publication Authors:
Publisher Info: Longline Environment Ltd.
Notes:
Related URLs:
Keywords: Carrying Capacity, Ecosystem Modeling, FARM, Puget Sound, Bivalve Shellfish, Geoduck, Aquaculture
Publication URLs: ecowin.org/geoduck
Abstract: Local-scale models such as FARM are a good tool to assess the environmental services of cultivated animals, and are easily applied, without requiring large volumes of data •Results from the FARM model indicate that geoduck and Manila clam aquaculture in Puget Sound providea combinedecosystem service corresponding to 90,000 population-equivalents (3.6 million USD) in reducing eutrophication •To the economic and social value of shellfish we have to add the ecosystem services they provide •Filter-feeders such as geoducks are not only a valuable product, but can be used as nutrient bioextractors, in a bioremediation role
Citation: Cubillo, Alhambra M., Joao G. Ferreira, Robert Marshall, Chris M. Pearce, Daniel Cheney, Bobbi Hudson, Andrew D. Suhrbier, William F. Dewey, Peter Becker, Shina Wysocki. 2015. Ecosystem goods and services of geoduck farming in South Puget Sound: A modelling analysis. Prepared for the Pacific Shellfish Institute by Longline Environment Ltd. 19 p.
Citation for Coverpage:
SG can post PDF online?: Yes
Uploaded File: EAS_Geoduck_Alhambra_Cubillo_2015.10.08.pdf

Application of the EcoWin model to shellfish culture in South Puget Sound
Publication Type: Technical Reports (non-peer-reviewed)
Publication Year: 2014
Publication Authors:
Publisher Info:
Notes:
Related URLs:
Keywords: Carrying Capacity, Ecosystem Modeling, FARM, EcoWin, Puget Sound, Bivalve

Shellfish, Aquaculture
Publication URLs: pacshell.org
Abstract: The implementation of EcoWin with (i) adaptation and if necessary development of biogeochemical and physiological process equations; (ii) spatial definition of the modeling domain; and (iii) coupling to hydrological and hydrodynamic models. Challenges and future directions.
Citation: Ferreira, Joao G. 2016. Application of the EcoWin model to shellfish culture in South Puget Sound. Prepared for Pacific Shellfish Institute, Olympia, WA by Longline Environment Ltd. 3 p.
Citation for Coverpage:
SG can post PDF online?: Yes
Uploaded File: EcoSim_application_for_SPS_Ferreira.pdf

Students Supported

No **Students Supported** information reported

Narratives

Planning for sustainable shellfish aquaculture in complex multiple use environments: Determining social and ecological carrying
Uploaded File: WSG_Carrying_Capacity_Narrative_PSI_4-2016.pdf

Partners This Period

Madrone Environmental Services
Types: Other
Scale: REGIONAL
Notes:

Longline Environment, LLC
Types: Other
Scale: INTERNATIONAL
Notes:

Washington Department of Ecology
Types: Government
Scale: STATE
Notes:

Washington State University Social & Economic Sciences Research Center
Types: Academic Institution
Scale: STATE
Notes:

Calm Cove Oyster Co.
Types: Industry/Business
Scale: REGIONAL
Notes:

Chelsea Farms
Types: Industry/Business
Scale: LOCAL
Notes:

Nisqually Indian Tribe
Types: Other
Scale: LOCAL

Notes:

Taylor Shellfish Farms
Types: Industry/Business
Scale: REGIONAL
Notes:

Baywater Shellfish Farm
Types: Industry/Business
Scale: LOCAL
Notes:

Arcadia Point Shellfish Co.
Types: Industry/Business
Scale: LOCAL
Notes:

Fisheries and Oceans Canada (DFO)
Types: Government
Scale: INTERNATIONAL
Notes:

National Marine Fisheries Service (US DOC, NOAA, NMFS)
Types: Government
Scale: FEDERAL or NATIONAL
Notes:

Washington Sea Grant
Types: Sea Grant Program
Scale: STATE
Notes:

STANDARD QUESTIONS

Community Hazard Resilience

No **Community Hazard Resilience** information reported

Economic Impacts

No **Economic Impacts** information reported

Impacts and Accomplishments

(1)

Type	impact
Title	Environmental remediation and room to grow: National Sea Grant-supported models assess the impacts of expanding shellfish aquaculture in South Puget Sound
	Washington produces a quarter of all U.S. farmed shellfish and wants to produce much more. But just how much can it grow sustainably? Determining

Relevance	carrying capacity would aid growers, facilitate dialog, and inform management and production decisions. Gauging shellfish's remediation role in removing nitrogen would also be valuable in South Puget Sound, the prime growing region, which suffers from increasing nutrient loads and low oxygen in some embayments.
Response	National Sea Grant-funded researchers considered physical, ecological, social and production capacities in determining South Puget Sound's shellfish carrying capacity. They incorporated farm production records, shellfish species metrics, water resource data, policy and regulation assessments, and stakeholder information. Ecopath modeling was used to create past and recent biomass snapshots of multiple plant and animal species and Ecosim modeling forecast changes out to the year 2054 according to various production and management scenarios. Researchers used Farm Aquaculture Resource Management (FARM) modeling to simulate shellfish growth, harvests, and algae and detritus removal.
Results	FARM modeling accurately predicted actual harvests. Ecopath modeling indicated current growing practices had neutral or beneficial effects on most key species' biomass. Doubling bivalve production, even increasing it 10 times in most cases, had little impact. Model results for South Puget Sound suggest shellfish harvest removed as much nitrogen as 40,000 humans produce, saving $1.6 million a year in waste treatment. The results helped researchers calculate the ecosystem services aquaculture provides, particularly in controlling eutrophication.
Recap	National Sea Grant-supported modeling in South Puget Sound suggests expanded shellfish production could help control eutrophication without adverse impacts on key marine species.
Comments	
Primary Focus Area	Sustainable Fisheries and Aquaculture
Secondary Focus Areas	Resilient Communities and Economies
Goals	Coastal communities and economies are vibrant and resilient.
Partners	Arcadia Point Shellfish Co. Baywater Shellfish Company Calm Cove Oyster Company Chelsea Farms Fisheries and Oceans Canada (DFO) Longline Environment, Ltd Madrone Environmental Services National Marine Fisheries Service (US DOC, NOAA, NMFS) Nisqually Tribe Taylor Shellfish Company Washington State Department of Ecology Washington State University Social & Economic

	Sciences Research Center
	Type accomplishment * Title Washington Sea Grant investigates social and ecological carrying capacity for shellfish aquaculture * Relevance Washington is the nation’s leading producer of bivalve shellfish, with harvests of about 40,000 metric tons annually, and South Puget Sound is a major growing area. The region also is experiencing rapid development, which has at times created conflicts between shoreline users and shellfish growers and illustrated the need for tools and information to inform regional planning and management of sustainable shellfish culture. * Response Funded through a national strategic initiative, Washington Sea Grant-supported researchers conducted an evaluation of South Puget Sound’s shellfish production and ecological and social carrying capacity. The research team applied comprehensive farm- and ecosystem scale models (e.g., FARM, EcoPath) to help shellfish farmers and harvesters, resource managers, and other interested parties identify, evaluate, and account for social and environmental considerations in shellfish aquaculture development. * Results Researchers analyzed farm production records, shellfish species metrics, and aquaculture related policies and regulations, and they completed a detailed review of regional industry constraints and incentives. They also examined nitrogen removal and natural shellfish recruitment. Information from a variety of sources was compiled and incorporated into the models, which also built upon and complement ongoing and recently completed efforts elsewhere in the region. Model outputs simulated and predicted future biomass and nutrient conditions for a wide range of farming and harvest scenarios. All findings were presented to stakeholders as reporting was completed. * Recap Washington Sea Grant-supported research investigated ecosystem conditions and perspectives —including human dimensions—that determine South Puget Sound’s carrying capacity for shellfish aquaculture. Comments Support conservation and sustainable use of living marine resources through effective and responsible approaches, tools, models and information for harvesting wild and cultured stocks and preserving protected species. Assist coastal communities and marine-dependent businesses in planning and making decisions that provide local and regional economic benefits, increase resilience and foster stewardship of social, economic and natural resources. Match priorities and goals of state and national shellfish initiatives. Primary Focus Area Healthy Coastal Ecosystems Secondary Focus Areas Resilient Communities and Economies Goals Ocean and coastal resources are managed using ecosystem-based approaches.,Coastal communities engage in comprehensive planning and sustainable

development. Partners Baywater Shellfish Farm Calm Cove Oyster Co. Chelsea Farms Longline Environment, LLC Madrone Environmental Services Nisqually Indian Tribe Little Skookum Shellfish Farms Taylor Shellfish Farms Washington Department of Ecology Washington State University Social & Economic Sciences Research Center ---------- Type accomplishment * Title Application of the Farm Aquaculture Resource Management (FARM) model to shellfish culture in South Puget Sound * Relevance The application of models for local-scale simulation of production and environmental effects assists managers and industry in promoting sustainable aquaculture, and facilitates stakeholder dialog. * Response The Farm Aquaculture Resource Management (FARM) model was applied to shellfish farms in Puget Sound to simulate growth, harvest potential, and removal of algae and detrital organics by filter-feeders. The results were used to calculate the environmental and economic contribution of the industry in Puget Sound with respect to ecosystem services, particularly with respect to the top-down control of eutrophication. * Results With respect to provisioning services, the model outputs were in general a good match to declared production. The value of regulatory services to the entire Sound is estimated to be in excess of three million dollars per year, or the nitrogen loading of 84,000 Population-Equivalents. * Recap Washington Sea Grant support enabled the application of state-of-the-art modeling tools to shellfish culture in South Puget Sound, and promoted stakeholder access to these tools. Farmers now understand better how mathematical models can be used to support the industry and help with sustainable growth. Comments Primary Focus Area Sustainable Fisheries and Aquaculture Secondary Focus Areas Healthy Coastal Ecosystems Goals Ocean and coastal resources are managed using ecosystem-based approaches.,Aquaculture operations and shellfish harests are safe, environmentally sustainable and support economically prosperous businesses.,The future workforce is skilled in discilines critical to coastal and ocean economies and ecosystem health. Partners Longline Environment, Ltd Washington Department of Ecology Chelsea Farms Taylor Shellfish Farms Fisheries and Oceans Canada (DFO) ---------- Type accomplishment * Title Ecological Carrying Capacity for South Puget Sound Ecopath with Ecosim * Relevance This work focused on several lower trophic level components of the South Puget Sound (SPS) food web. A key aspect of this approach was the unique application to multi-species and commercially important aspects shellfish aquaculture and harvest. Simulations forecasted potential future ecosystem configurations under a variety of population changes and fishing and

PI Draft	aquaculture management policies. * Response The Ecopath with Ecosim (EwE) modeling framework provided a way to visualize the biomass of a suite of species groups over time, using mortality rates or ‘production’ of species groups, food intake and diet composition. The SPS EwE model simulated known historic changes for 1970-2012, and forecasted potential changes through 2054 for 12 key species of marine mammals, marine birds, salmon, game fish and bivalves. * Results Analyses of the 1970 and 2012 mass balance models suggested that the rapid expansion of shellfish aquaculture would not likely have significantly influenced the biomasses of other species. In all scenarios of future marine production, there were few trophic effects on the South Puget Sound ecosystem when maintaining or significantly increasing shellfish aquaculture production. * Recap Washington Sea Grant-supported research applying existing ecosystem models to shellfish aquaculture production in South Puget Sound, and an in-depth examination of the current and future effects of production/harvest changes on critical marine organisms. Comments See: Central Puget Sound Ecopath/Ecosim model biological parameters - Developing food web models for ecosystem-based management applications in Puget Sound (NMFS, http://www.nwfsc.noaa.gov) for an earlier modeling study in Puget Sound. Primary Focus Area Sustainable Fisheries and Aquaculture Secondary Focus Areas Healthy Coastal Ecosystems Goals Ocean and coastal resources are managed using ecosystem-based approaches.,Ocean and coastal habitats are protected, enhanced and restored.,Aquaculture operations and shellfish harests are safe, environmentally sustainable and support economically prosperous businesses.,Fisheries are safe, responsibly managed and economically and culturally vibrant. Partners Madrone Environmental Services Washington Department of Ecology Taylor Shellfish Farms Fisheries and Oceans Canada (DFO) National Marine Fisheries Service (US DOC, NOAA, NMFS) Washington Sea Grant ---------- Type impact * Title Washington Sea Grant investigates the production and ecological carrying capacities for shellfish aquaculture in south Puget Sound * Relevance Washington State is the largest producer of hatchery-reared and farmed shellfish in the U.S, accounting for 25% of the total domestic production by weight, with an annual value exceeding $107 million. To address questions regarding sustaining and increasing shellfish production in the state we applied an expanded definition of carrying capacity to integrate interrelated elements of 1) physical, 2) production, 3) ecological and 4) social carrying capacities. This Sea Grant funded research applied an interdisciplinary approach to simulate shellfish production and environmental effects to assist

growers, facilitate public dialog and inform management and production decisions. * Response Farm production records and shellfish species metrics, water resource data, assessments of aquaculture-related policies and regulations, and information from stakeholder groups were incorporated in ecosystem and farm-scale models to assist in simulating future carrying capacities for bivalve shellfish farming and harvest scenarios in the south Puget Sound area of Washington state. “Ecopath” with “Ecosim” modeling provided a way to visualize the biomass of a suite of species in south Puget Sound. Ecopath created biomass balanced snapshots for 1970 and 2012 of multiple plant and animal species. Ecosim was then used to forecast to 2054 future changes in selected plants and animals relative to various aspects of shellfish aquaculture production and natural resource management. The “FARM” model was applied to simulate shellfish growth, harvest potential, and removal of algae and detrital material at the farm-scale. The results were used to calculate the environmental and economic contribution of the industry in south Puget Sound with respect to ecosystem services, particularly with respect to the top-down control of eutrophication by shellfish. An Assessement of Estuarine Trophic Status (ASSETS) model was used to update the eutrophication status in south Puget Sound, including the factors influencing development of eutrophication, and nutrient related water quality conditions. * Results Ecopath modeling indicated current shellfish production and management practices were beneficial or not harmful to biomass changes of almost all key species in south Puget Sound. Fisheries and aquaculture policies generally had the effect of allowing for rebuilding biomasses in species that had declined from 1970 to the present. In all scenarios of future marine production, trophic effects on the south Puget Sound ecosystem were largely driven by changes in phytoplankton production. Increasing overall south Puget Sound bivalve aquaculture by a factor of 2 (in most cases to 10) had little effect on the other key species modeled. The FARM model forecasted shellfish production of 3,700 to 47,300 kg valued at $23,000 to $122,000 per culture cycle from four small to medium sized oyster and Manila clam farms in south Puget Sound. The harvest from a similarly sized geoduck farm was forecasted to be 14,600 kg with a farmgate value of $608,000. A larger raft-culture mussel farm had a modeled output of 814,800 kg valued at $2,171,000. In general, these model outputs were in close agreement with declared harvest figures. Shellfish harvest also reduces nutrient enrichment through consumption of phytoplankton and detrital material. Harvest at the six modeled south Puget Sound farms removed about 40 tons of nitrogen per year. The reported south

	Puget Sound shellfish harvest (2013 data) was estimated to remove over 130 tons of nitrogen per year, which is equivalent to the nitrogen loading of nearly 40,000 humans. The value of waste treatment plant cost savings to the entire south Puget Sound was estimated to be 1.6 million dollars per year. ASSETS modeling for 2007 and 2015 showed south Puget Sound continues to experience an increasing level of nutrient loading. This is indicated by current chlorophyll and macroalgal observations, as well as the occurrence of toxic algae blooms. On the other hand, dissolved oxygen depletion does not appear to be a south Sound-wide problem, although it does occur in some embayments. The combined indicators suggest that nutrient management measures should continue, including innovative measures such as the use of shellfish aquaculture, to remediate continued worsening conditions. * Recap Washington Sea Grant-supported research applying existing ecosystem models to shellfish aquaculture production in south Puget Sound, and an in-depth examination of the current and future effects of production/harvest changes on critical marine organisms. These products will help shellfish farmers and harvesters, resource managers, and other interested parties identify, evaluate, and account for social and environmental considerations in shellfish aquaculture development. Comments 1) Support conservation and sustainable use of living marine resources through effective and responsible approaches, tools, models and information for harvesting wild and cultured stocks and preserving protected species. 2) Assist coastal communities and marine-dependent businesses in planning and making decisions that provide local and regional economic benefits, increase resilience and foster stewardship of social, economic and natural resources. 3) Match priorities and goals of state and national shellfish initiatives. Primary Focus Area Healthy Coastal Ecosystems Secondary Focus Areas Goals Partners

Leveraged Funds

No **Leveraged Funds** information reported

Meetings, Workshops, Presentations

(1)

Type of Event	Public or professional presentation
Description	PCSGA 2015 -- What Effect Does Shellfish Culture Really Have on the South Puget Sound Ecosystem? Bobbi Hudson, David Preikshot, Daniel Cheney and Teri King. PCSGA/NSA-PCS Annual Meeting, Hood River, OR.

Event Date	09-29-2015
Number of Attendees	150

(2)

Type of Event	Public or professional presentation
Description	NSA 2015 -- Shellfish Farming in the Pacific NW Public and Stakeholder Perceptions. Bobbi Hudson, Thom Allen and Danna Moore. NSA Annual Conference, Monterey, CA.
Event Date	03-27-2015
Number of Attendees	100

(3)

Type of Event	Public or professional presentation
Description	WAS/NSA 2016 -- Physical and Social Dimensions of Shellfish Aquaculture on the U.S. West Coast. Bobbi Hudson, Thom Allen, Danna Moore, Andrew Suhrbier and Hannah Faulkner. WAS 2016, Las Vegas, NV.
Event Date	02-24-2016
Number of Attendees	100

(4)

Type of Event	Public or professional presentation
Description	European Aquaculture Society 2015 -- ECOSYSTEM GOODS AND SERVICES OF PACIFIC GEODUCK FARMING IN SOUTH PUGET SOUND?A MODELLING ANALYSIS. Alhambra M. Cubillo, Joao G. Ferreira*, Robert Marshall, Chris M. Pearce, Daniel Cheney, Bobbi Hudson, Andrew D. Suhrbier, William F. Dewey, Peter Becker, Shina Wysocki. EAS 2015. Rotterdam, Netherlands.
Event Date	10-23-2015
Number of Attendees	150

(5)

Type of Event	Sea Grant-sponsored/organized event
Description	EcoPath Workshop -- Visualizing Ecological Interactions of South Puget Sound Research Overview. Bobbi Hudson, David Preikshot, Daniel Cheney and Teri King. LOTT Clean Water Alliance, Olympia, WA.

Event Date	01-27-2016
Number of Attendees	50

Tools, Technologies, Information Services / Sea Grant Products

No **Tools, Technologies, Information Services / Sea Grant Products** information reported

NOAA SEA GRANT AQUACULTURE RESEARCH PROGRAM: FINAL REPORT

Planning for sustainable shellfish aquaculture in complex multiple use environments: Determining social and ecological carrying capacity for south Puget Sound, Washington

Principal Investigator:

Daniel Cheney, Pacific Shellfish Institute, Olympia, WA

Co-Investigators:

Bobbi Hudson, Pacific Shellfish Institute, Olympia, WA
Joao Ferreira, Longline Environment, Ltd., London, United Kingdom
David Preikshot, Madrone Environmental Services, Duncan BC, Canada
Joth Davis, Baywater Inc., Bainbridge Is., Washington
Teri King, Washington Sea Grant Extension, Seattle, WA
Mindy Roberts, Washington Dept. of Ecology, Olympia, WA
Thom Allen and Danna Moore, WSU Social and Economic Research Center, Pullman, WA
Suzanne Bricker, NOAA National Ocean Service, Silver Spring, MD

Introduction and Background

Analyses of Bivalve Shellfish Carrying Capacity

Bivalve shellfish are one component complex estuarine ecosystems, and shellfish production is one of many uses of the ecosystem. The interplay of these elements is considered under an Ecosystem-Based Management (EBM) approach, defined as: an integrated approach to resource management that considers the entire ecosystem, including humans, and the elements that are integral to ecosystem function. A similar approach, specific to aquaculture, has been defined as an Ecosystem Approach to Aquaculture (EAA), and carrying capacity is a tool to achieve an EAA.

To adequately address questions of shellfish aquaculture sustainability in the context of EMB and multi-use spatial planning, an expanded definition of carrying capacity must include the interrelated and co-dependent elements of 1) physical, 2) production, 3) ecological and 4) social carrying capacities. This approach to carrying capacity ensures an interdisciplinary method because of the multiple types of expertise required. It also ensures an integration of environmental and socio-economic ecosystem-based tools, which is especially important in multi-use coastal ecosystems to communicate between the scientific, management and local communities.

Study Goals and Objectives / Rationale

The goal of this research was to advance the integration of shellfish aquaculture in the complex multiple use environment of south Puget Sound (SPS) through a Production, Ecological, and Social Capacity Assessment (PESCA) through the following objectives:

- Calculate production and ecological carrying capacity at the farm scale.
- Evaluate ecological carrying capacity at the ecosystem scale.
- Examine the social carrying capacity for bivalve shellfish aquaculture.
- Engage shellfish farmers and other stakeholders in the process to apply this three-tiered carrying capacity approach.

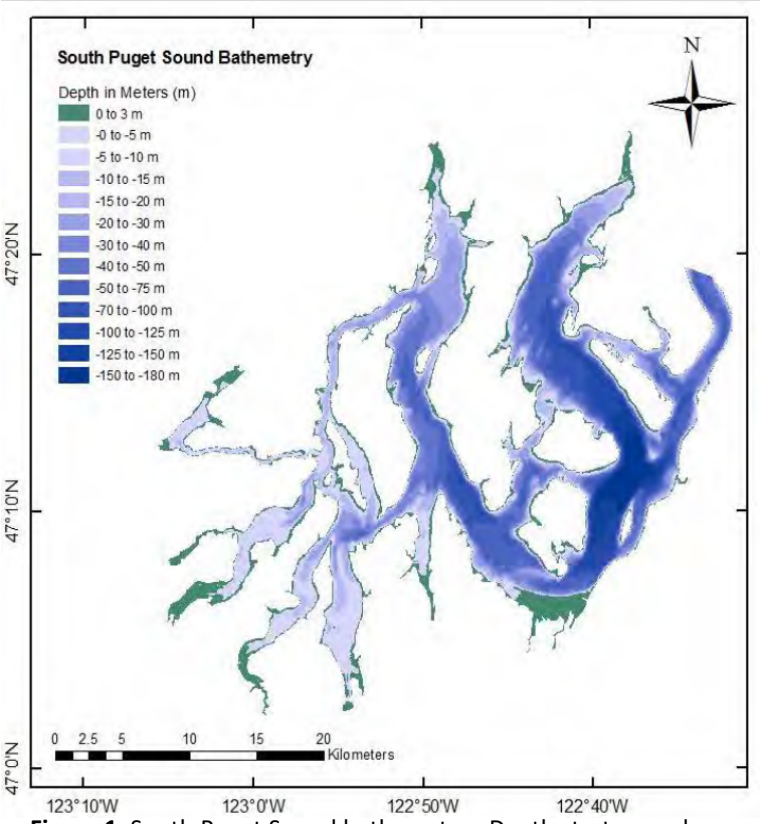

Figure 1. South Puget Sound bathymetry. Depth strata are shown as darker blue with increasing depth or as green for the stratum between mean low water and highest high tide.

Description of the Study Site

South Puget Sound (SPS), defined as the Puget Sound Basin south of the Tacoma Narrows, is an approximately 450 km^2 water body, with a number of small and relatively shallow water inlets (**Figure 1**). Extensive tidal exchange, freshwater inputs from both forested and urban lands, and a human population within the watershed of about 260,000 are principal pressures driving water quality. Highly productive, the extensive intertidal habitat, complex shape and circulation patterns of SPS produce highly variable temperature, dissolved oxygen and salinity patterns. These features create generally favorable conditions for the production and cultivation of bivalve shellfish.

Shellfish cultivation and practices

From a regional and national perspective shellfish aquaculture is poised to become a dominant player in the U.S. seafood industry. Production on the west coast has increased steadily over the last 30 years, with new species, such as the geoduck clam, seeing expanding domestic and export demands. Shellfish production on both private and public lands has been a traditional activity in Washington State since the 1860's and extensive estuarine areas in the state are currently used for commercial cultivation of oysters (*Crassostrea gigas, Crassostrea virginica* and others), Manila clams *(Ruditapes philippinarum*), geoduck clams (*Panope generosa*) and mussels (*Mytilus* spp.). Shellfish aquaculture plays an increasingly important role in domestic seafood production: Washington State is the largest producer of hatchery-reared and farmed shellfish in the U.S, accounting for 25% of the total domestic production by weight, with an annual farmgate value exceeding $107 million. SPS produces one-third to one-half of Washington's shellfish production, and by value approximately $45 million per year at the farmgate.

Methods

Overview of Approach

PESCA utilized existing and newly acquired local and regional data, predictive modeling tools, and regulatory, policy, and stakeholder guidance to: a) guide and inform business and regulatory decisions regarding farm siting, density, and methods; b support multi-use spatial planning at county, state, and federal levels related to shellfish aquaculture; and c) socio-economic research building on current and past NOAA supported projects targeted to understand shellfish aquaculture in a larger context.

Modeling Tools

Farm Aquaculture Resource Management model (FARM)

FARM used individual growth models to relate shellfish growth to the characteristics of the culture environment. The objective of this part of the work was to apply models for four shellfish species cultivated in SPS: the geoduck *Panope generosa*, the Pacific oyster *Crassostrea gigas*, the Manila clam *Ruditapes philippinarum*, and the Mediterranean mussel *Mytilus galloprovinciallis*. A net energy balance approach was used, and calibration was carried out for local conditions and validated using in-situ culture practice data. For geoduck, where no physiological growth model was available, equations were drawn from the literature and experimental studies. The development of the individual growth model for geoduck was presented in a separate report. The work presented here focused on case studies for the three other shellfish species: Pacific oyster, Manila clam, and Mediterranean mussel.

The FARM model simulated processes at the farm-scale by integrating a set of different sub-models: i) hydrodynamic and particle settling (for suspension culture); ii) biogeochemical; iii) shellfish growth models, and iv) ASSETS eutrophication screening model.

Three different types of outputs were obtained with FARM, focusing on people (production), planet (environmental externalities), and profit. The FARM outputs are production, average physical product (a proxy for return on investment), income, expenditure, gross profit, biodeposition, nutrient emission and eutrophication assessment.

Existing individual models were calibrated for environmental drivers local to the cultivation area. After the individual models for the three species were calibrated for local conditions, the appropriate adaptations were made to the FARM model to enable farm-scale runs to be carried out each case studies. A total of six farm-scale models were set up in FARM, of which results were provided for three species at five locations. Geoduck simulations were presented in a separate report, which described model conceptualization and implementation.

Additional details and figures of FARM model development and application are presented in the SPS project reports – Cubillo, et al. 2015 (geoduck), Ferreira, et al. 2016 (oysters, clams and mussels).

EcoWin Model

EcoWin is a well-established framework for dynamic ecological modeling of coastal systems and complementary to approaches such as EcoPath. EcoWin is employed to resolve hydrodynamics and biogeochemistry, and can also include an analysis of the population dynamics of selected species. For the purpose of this project, EcoWin was to be used to simulate hydrodynamics, biogeochemistry, and aquaculture for the SPS ecosystem, utilizing the data sourced from the state and federal resource agencies (USGS, NOAA, NODC, WDOE), regional shellfish growers, and PSI field studies. This model was designed to create a detailed ecosystem-scale simulation of the interactions taking place during shellfish cultivation. The implementation of EcoWin in SPS required hydrodynamic data obtained from the Washington Department of Ecology (WDOE). Those data, appropriately upscaled and verified for consistency, in particular with respect to mass conservation, were then supplied to the ecosystem modelers. Unfortunately, for this application, those data could not be utilized in the EcoWin model, and further data correction and analysis was outside the scope of this phase of the study. Therefore,

full implementation of EcoWin will be dependent on the necessary completion of this final stage at a later date.

See: Ferreira (2016) for additional information.

EcoPath / EcoSim (EWE) Model

We built a dynamic simulation model of the South Puget Sound (SPS) marine ecosystem to emulate known historic changes from 1970 and 2012 and to forecast potential changes, between 2012 and 2054, of the biomass of 12 key species of marine mammals, marine birds, salmonids, game fish and bivalves. Historic simulations were tuned by fitting hind-cast annual average biomass changes of birds, mammals, fish and bivalves to data from stock assessments of abundance surveys.

The fits of these historic biomass changes were optimized by estimating parameters controlling predator-prey dynamics and by estimating a time series of annual Primary Production Anomalies (PPAs) of phytoplankton in the model. Simulations were then conducted from 1970 to 2054 to forecast potential future ecosystem configurations. Forecasts were simulated by varying future phytoplankton productivity, changes in abundance of mediating species, and changes in certain fisheries and aquaculture management policies. The simulations using this dynamic model were initiated with a steady state Ecopath model of SPS parameterized for the year 1970. We also built a steady state Ecopath model of SPS parameterized for 2012 as a means of comparison to the simulation results and the 1970 steady state model.

An important aspect of our approach to forecasting was the use of Multisim, a subroutine within Ecosim which allowed us to run 100 simulations of the future for each scenario we examined. From these simulations we then examined changes in biomass of the species groups between 2012 and 2054. These groups were selected by the modelling team after consulting with representatives of local commercial shellfish harvesters, growers, and governmental agencies. They were deemed to provide sufficient resolution to meaningfully explore management policy options in simulations of SPS in the future in the Ecosim component of the modelling exercise.

The chief source of ecosystem variation in forecasting scenarios was time series of PPAs. We developed a model which resamples the hind-cast 1970-2012 PPA to create simulated SPS PPAs. These PPAs replicate three aspects of the time series: long-term mean value, interannual variability, and decadal variations. Scenarios for management policy options and ecosystem manipulations were then run 100 times. The simulations were grouped into two families: 1) examining feedbacks that may occur in the SPS ecosystem due to naturally occurring shifts in the biomass of a given mediating species group; and 2) examining feedbacks that may occur in the SPS ecosystem due to changes in a particular fishing or aquaculture management policy.

Additional details of model development and application are presented in the SPS project report – Preikshot, et al. 2016.

Stakeholder Surveys

Information on constraints and incentives for shellfish aquaculture in the region was gathered in Year 1 through PSI and shellfish industry assessments of aquaculture-related policies and regulations. This

information was updated in Year 2 to conform to the latest shoreline management guidance currently being finalized for south Puget Sound counties.

Three stakeholder meetings were completed as part of informational data collection sessions (meetings 1 and 2), and presentation of project findings for EWE modeling. All meetings were facilitated by Teri King, University of Washington Sea Grant.

A survey was designed to assess perceptions and behaviors related to shellfish and shellfish farming, and to examine what influences social attitudes toward these activities. An Advisory Committee comprised of local, state, and federal resource managers, planners, and industry representatives was assembled by PSI to guide survey development. The survey was implemented by Washington State University's Social and Economic Research Center, along with a companion stakeholder survey for a separate but related NOAA Sea Grant Aquaculture Research Program project. For this project, the survey "Shellfish Farming and Your Community" (**Figure 2**) was implemented in six Washington counties: Skagit, Kitsap, Pacific, Thurston, Pierce, Mason. (Under PSI's companion project, four additional counties were survey, within Oregon and California.) Survey questions were designed to gauge:

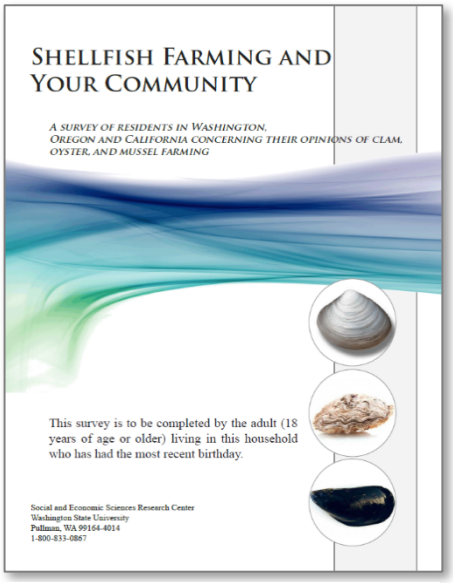

Figure 2. Stakeholder survey cover.

- How do these communities understand, value, and respond to shellfish farming?
- What factors and sources of information influence these social attitudes and values?
- What kinds of outreach might be most effective at improving public awareness of shellfish farming?

The population for the survey consisted of all residential households within the 10 county study area. A total of 862,187 residential households were identified by Genesys Sampling Inc., and a random sample of 4,000 households were selected. Residents were first asked to complete the survey online, but those who did not respond to the web survey were later sent a paper version of the questionnaire.

Results and Discussion

Farm Aquaculture Resource Management model (FARM)

The simulated outputs for Pacific oyster culture at the two farm sites showed a relatively good match to the declared harvest (**Table 1**). The role of the Totten Inlet oyster farm in nutrient removal is shown in **Figure 3**, which represents the annualized mass balance of the culture. There was a net removal of 265 kg of nitrogen, which equated to 0.7% of the total live weight biomass produced.

Considerably different results were obtained from a large Mediterranean mussel farm in Totten Inlet. Both the area and the stocking density were an order of magnitude higher than the oyster and clam farms, and this is reflected in the food depletion simulations. FARM indicates a significant reduction in chlorophyll of over 12%, which means that farm plays an important role in mitigating eutrophication.

Table 1. Production effects of two Pacific oyster farms in SPS (per production cycle)

Variable	Eld Inlet	Totten Inlet
Model inputs: Seeding (kg)	800	1,000
Model outputs: Total harvest (kg)	23,000	38,723
Actual outputs: Declared harvest (kg)	19,395	47,343
ASSETS: eutrophication model score (in to out)	4-no change	4-no change

An assessment of the role of the three species of bivalves in mitigating eutrophication is shown in **Table 2**. The numbers can be combined with simulations executed for Manila clam in North Puget Sound, geoducks in SPS, and extended to other shellfish harvesting areas of the United States. This would for the first time allow a budget to be made of the role of bivalve shellfish in controlling eutrophication at a national scale.

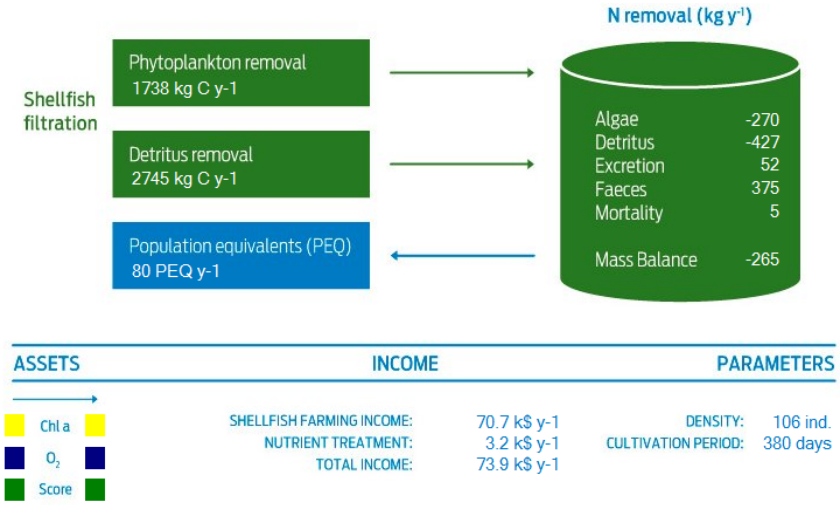

Figure 3. Mass balance for culture of Pacific oysters in Totten Inlet.

Table 2. Environmental externalities from bivalve culture in SPS (FARM case study outputs)

	Pacific oyster		Manila clam		Mediterranean mussel
	Eld Inlet	Totten Inlet	Eld Inlet	Little Skookum	Totten Inlet
Culture cycle (days)	365	380	1240	840	400
Production (kg cycle-1)	22999.72	38723.10	3449.68	18484.74	868570.29
Annualized production (kg y-1)	22999.72	37194.56	1015.43	8032.06	792570.39
Net nitrogen removal (kg N y-1)	167	265	94	380	38900
Percentage N / live weight (%)	0.73	0.71	9.26	4.73	4.91
Population-Equivalents	51	80	29	115	11788
Potential nutrient credits (USD)	2040	3200	1160	4600	471500

EcoPath / EcoSim (EWE) Model

Mass balance and MTI modeling: The mass balance models of South Puget Sound in 1970 and 2012 catalogued the changes that occurred in the biomass of several marine species of biological, cultural and economic significance. Diagrams of the biomasses and trophic links simulated by the 2012 Ecopath model can be seen in **Figure 4**. Not all species are known to have exhibited significant biomass changes in SPS between 1970 and 2012. In the case of relative biomass change within species groups between 2012 and 1970, the largest gain was seen in farmed geoduck clams, sea lions, harbor seals, pink salmon, and chum salmon, **Figure 5**. The dynamic historic model reinforces the assumption that shellfish aquaculture had significant room to grow between 1970 and 2012 without interfering with the energetic dynamics of wild species in South Puget Sound.

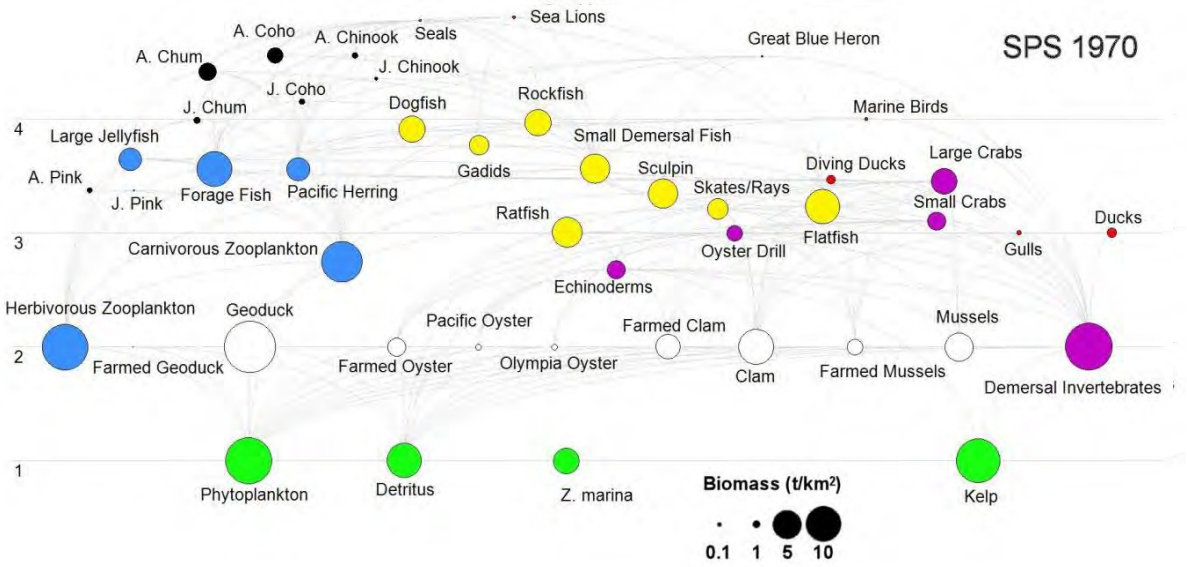

Figure 4: Trophic web of the SPS ecosystem in 1970. Circle area is proportional to the logarithm of biomass, grey lines show predator/prey linkages. Trophic level is labelled on the left. Groups are color coded to indicate niche similarities: red=marine mammals and birds, black=Pacific salmon, yellow=demersal fish, blue=forage fish and zooplankton, white=bivalves, purple=benthic invertebrates and green= primary producers.

A mixed trophic interactions (MTI) subroutine was employed to assess the effects that increasing the biomass of a given species, or magnitude of a fishery or harvest, will have on other groups in the model. When considering the effect of bivalve aquaculture operations on other groups in the model, it is interesting to note that there appears to few negative feedbacks, the exception being some of the wild bivalve species groups. A detailed discussion of the MTI model results is provided in the full research report.

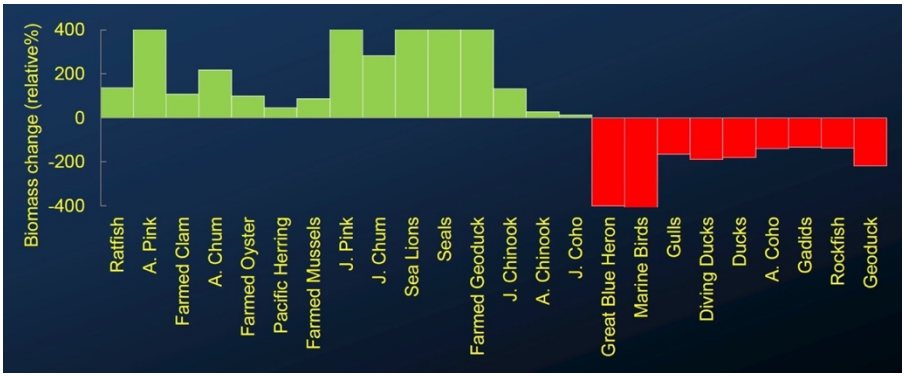

Figure 5. Modeled relative biomass change within species groups: 1970-2012.

Ecosim modeling: Ecosim scenarios were run in a module of Ecosim called Multisim. Multisim allowed us to run iterative simulations of the future to generate a probability distribution of future outcomes in several Ecopath parameters. An example of relative biomass changes for 100 simulations for 12 scenarios of management policy changes for 6 of 12 key species groups is shown in **Figure 6.**

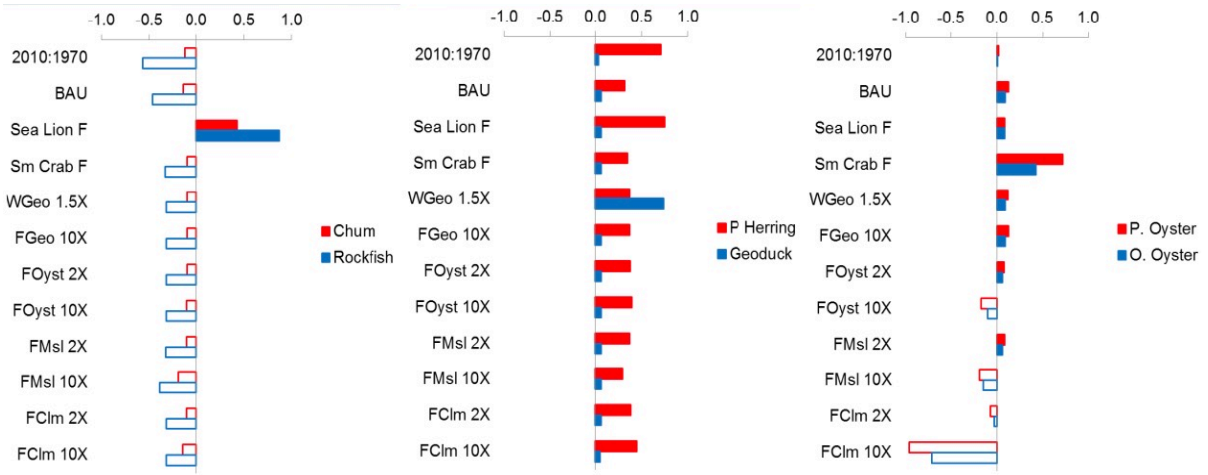

Figure 6. Relative change in biomass for 6 of the 12 focal species for 12 scenarios of management and production changes between 2012 and 2054 in which future phytoplankton production and variation is similar to that modelled for 1970-2010. Baseline Ecosim changes from 1970-2010 are also shown for comparison. Bars show average value from 100 simulations of each scenario.

Multisim modelling suggests bivalve aquaculture is generally benevolent at the scale of SPS as a whole. However, this does not mean that within some of the bays and inlets where aquaculture is concentrated there will be no effects on some species. Such meso-scale effects may be modelled more effectively with a spatial modelling tool like Ecospace. The observation that increasing clam aquaculture by an order of magnitude could result in decrease biomass of wild oysters may suggest the kinds of effects that may be seen at smaller scales within SPS.

Having established a biological modelling baseline, it would be invaluable to invoke the economic modelling capacity of Ecosim to examine potential trade-offs not only between different fisheries but also between the cost of a given management policy versus its benefit in species biomass. Such questions could be of particular value when examining the value of increases to wild geoduck clam biomass or whether or not to devote economic and social capital to expanding extant kelp and eelgrass habitat.

Finally, the business as usual or 'BAU' scenario, was beneficial or not harmful to biomass changes of almost all key species, and current fisheries and aquaculture policies generally have the effect of allowing for rebuilding biomasses in species that had declined from 1970 to the present.

Stakeholder Surveys

During the study period, 652 surveys were collected online and another 598 were mailed in, resulting in a 34% response rate (**Table 3**). Sampling error, or the degree to which the randomly selected sample of respondents represents the population from which it is drawn, was calculated at ±3%. At the time of the survey U.S. Census data estimates 1,519,653 adults lived in the ten county study area.

Results of the survey were detailed in "Public Opinion of Shellfish Farming: A report on the public perception of shellfish aquaculture in select counties in Washington, Oregon and California" and distributed to stakeholders across the three states and available on the PSI website (www.pacshell.org). Overall, the survey revealed limited knowledge of shellfish aquaculture, but a considerable level of support for policies supporting shellfish aquaculture and increased domestic seafood production. When

questioned if nearshore aquaculture production in their state should be increased, decreased, or stay the same, a preference for increased production outnumbered decreased production by a factor of nearly 5 to 1. Survey respondents also recognize the benefits of shellfish aquaculture, especially for providing locally produced seafood, creation of jobs, improving the local and state economy, and relieving pressure on wild fisheries.

Table 3. Summary statistics for the survey's ten county study region. Washington counties were the focus for this project, while Oregon and California counties were conducted under a companion PSI project funded by NOAA Sea Grant Aquaculture Research Program.

Study Area	Sample Size	Completed Surveys	Response Rate	Sample Error	Households in Area
Total Study Area	4,000	1,250	34%	±3%	862,187
Washington Study Area	2,400	770	35%	±4%	640,462
Skagit	400	129	34%	±9%	51,473
Kitsap	400	131	36%	±9%	107,367
Pacific	400	150	42%	±9%	15,547
Thurston	400	125	33%	±9%	108,182
Pierce	400	109	29%	±9%	325,375
Mason	400	126	35%	±9%	32,518
Oregon Study Area	800	282	38%	±6%	48,952
Tillamook	400	145	39%	±9%	18,359
Coos	400	137	37%	±9%	30,593
California Study Area	800	198	26%	±7%	172,773
Humboldt	400	103	27%	±9%	61,559
Marin	400	95	24%	±9%	111,214

This research indicated there was great potential for increased education and outreach regarding shellfish related activities. Survey responses suggested that the most effective means to share information will be television, newspapers and websites, as well as booths at public events.

Summary of Outreach and Information / Technology Transfer

Project results were transferred to a broad range of audiences, including local, state and federal agencies, academia, and shellfish growers. The tools developed by this project were were presented to those in the aquaculture industry and to researchers and others interested in applying these tools. Stakeholders were engaged from the beginning of ecosystem carrying capacity modeling, and workshops presenting findings were extended to additional stakeholders, including local government, shellfish growers and environmental groups. Technical reports as well as presentations at local, regional, national and international meetings [including but not limited to informational sessions at WSG's annual Shellfish Growers Conference, the joint Pacific Coast Shellfish Growers Association (PCSGA)/National Shellfisheries Association (NSA) annual meeting, the NSA annual meeting, and the World Aquaculture Society (WAS) annual meeting] were developed for distributing the information to the scientific and aquaculture communities.

The following short, medium and long term outcomes are predicted to result from this project:

Short-term outcomes: Optimization of aquaculture operations based on model outputs and stronger community and local government awareness of trade-offs and environmental effects; increased awareness among resource managers of the potential application of models and scenario development; and increased public understanding of and engagement in modeling process and ecosystem interactions.

Medium-term outcomes: Scientists use study results and guidance materials to support promote sustainable aquaculture practices that also improve water quality; enhanced capacity among decision-makers to plan for and support sustainable shellfish aquaculture; baseline results are used as fisheries reference to manage coastal resources; and politicians pass legislation to include aquaculture as acceptable water quality management measure, potential nutrient trading component.

Long-term outcomes: Increased public support for shellfish aquaculture; and expanded sustainable shellfish aquaculture and improved water quality in South Puget Sound and throughout the region.

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