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

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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.

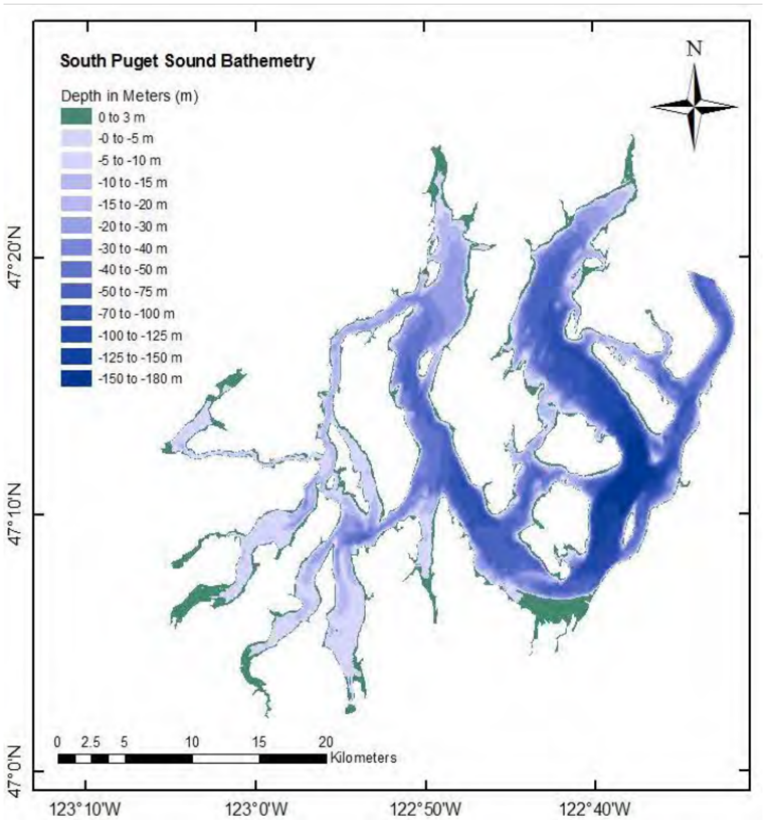

Figure 1. South Puget Sound bathymetry. Depth strata are shown as darker blue with increasing depth or as green for the stratum between mean low water and highest high tide.

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:

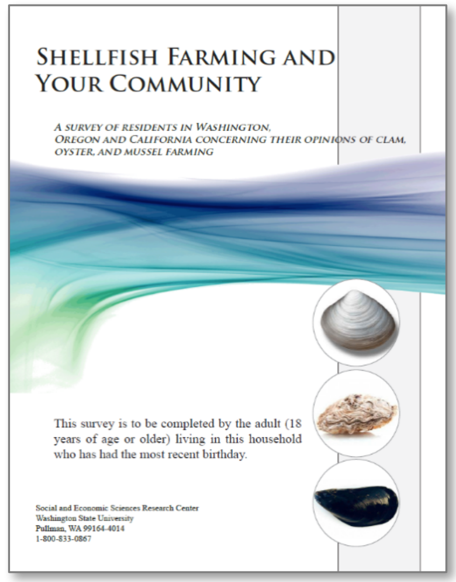

Figure 2. Stakeholder survey cover.

- 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.

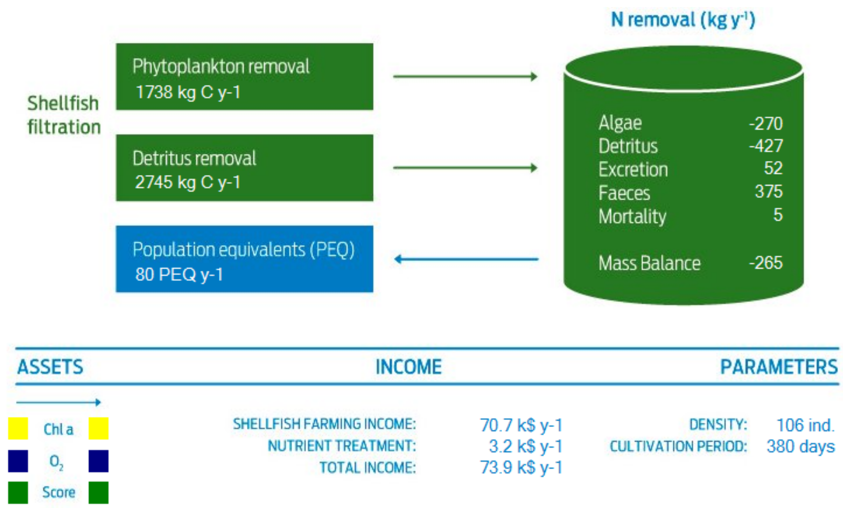

Figure 3. Mass balance for culture of Pacific oysters in Totten Inlet.

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.

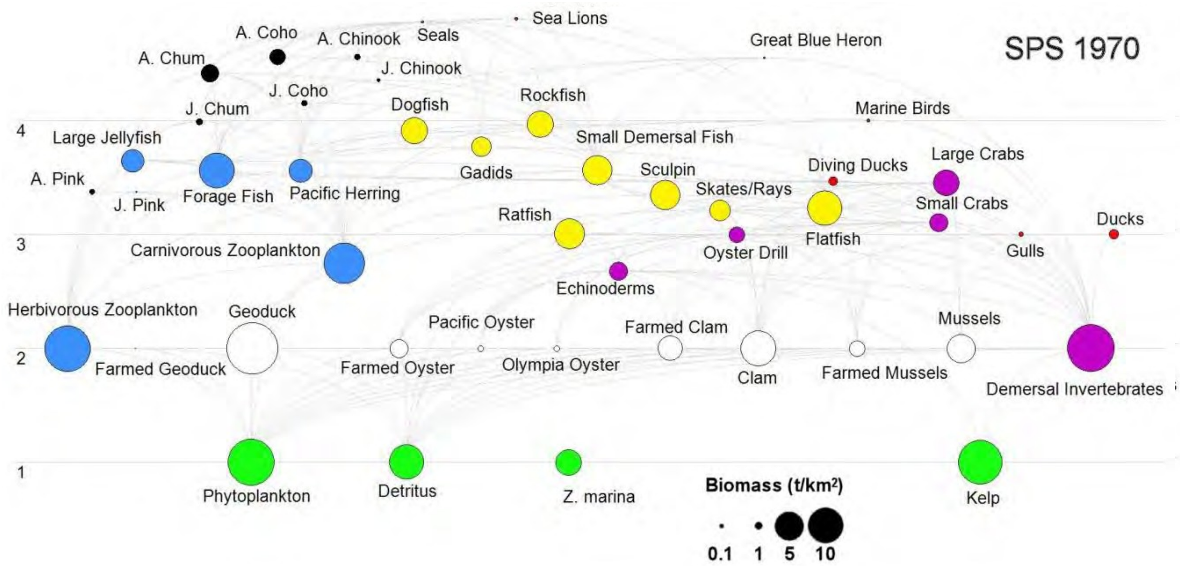

Figure 4: Trophic web of the SPS ecosystem in 1970. Circle area is proportional to the logarithm of biomass, grey lines show predator/prey linkages. Trophic level is labelled on the left. Groups are color coded to indicate niche similarities: red=marine mammals and birds, black=Pacific salmon, yellow=demersal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

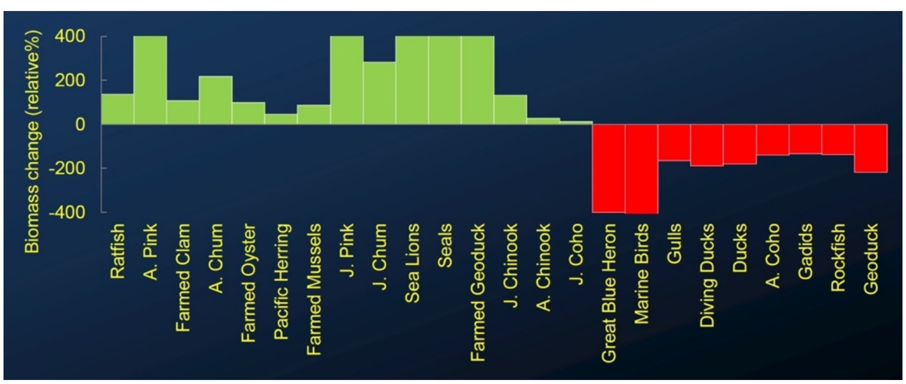

Figure 5. Modeled relative biomass change within species groups: 1970-2012.

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.**

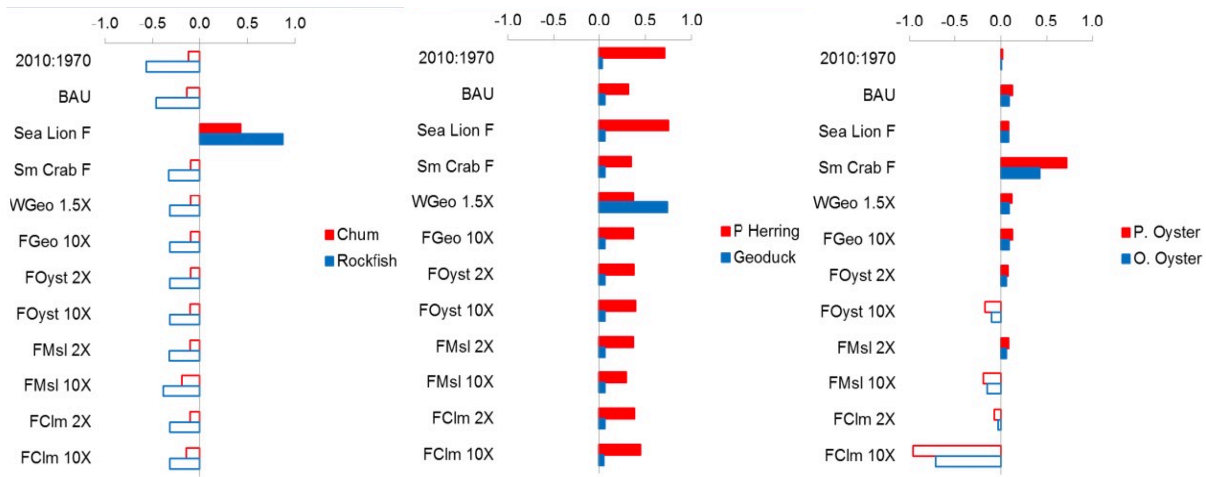

Figure 6. Relative change in biomass for 6 of the 12 focal species for 12 scenarios of management and production changes between 2012 and 2054 in which future phytoplankton production and variation is similar to that modelled for 1970-2010. Baseline Ecosim changes from 1970-2010 are also shown for comparison.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