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

Joao G. Ferreira, Alhambra M. Cubillo, Daniel Cheney, Bobbi Hudson, Andrew D. Suhrbier, William F. Dewey, Shina Wysocki

LONGLINE ENVIRONMENT

Table of Contents

Summary

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.

The simulation results obtained in this work were scaled to Puget Sound in order to assess the role of shellfish in eutrophication abatement. The value of these regulatory ecosystem services is estimated to be in excess of three million dollars per year, based on the cheapest nutrient removal alternative at source. Since non-point sources are likely to constitute a significant proportion of the nutrient loading, source control becomes significantly more costly, and the role played by shellfish in top-down control of eutrophication is increasingly relevant.

Introduction and objectives

The Production, Ecological, and Social Carrying Capacity Assessment (PESCA) project identified as its first objective: *calculate production and ecological carrying capacity at the farm scale*. In this context, Task 1 was defined as: *model the effects of shellfish production on key ecological variables, and estimate the value of nitrogen removal.*

The role of bivalve shellfish in improving water quality has not been widely recognized until the last decades (e.g. Higgins et al., 2011), although the filtration of water column particulates by different bivalve species has been studied for the best part of a century (Orton, 1928; Jørgensen, 1943; Loosanoff & Tommers, 1948; Carriker, 1959; Tenore & Dunstan, 1973; Shumway & Cucci, 1987; Jørgensen et al, 1990; Bayne et al., 1993; Clausen & Riisgård, 1996).

South Puget Sound (SPS) is defined as the Puget Sound Basin south of the Tacoma Narrows: it is a 449 km^2 water body, with a number of small and relatively shallow water inlets. 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 on water quality. Although shellfish aquaculture production has been trending upward in SPS due to a demand for product and improved production methods, this trend is countered by a decrease in culture areas due to declining water quality, regulatory concerns over habitat use by intensive aquaculture, aesthetic concerns, and other user conflicts. However, shellfish production and harvest can help to offset effects of low dissolved oxygen and elevated nutrient levels (Bricker et al., 2007).

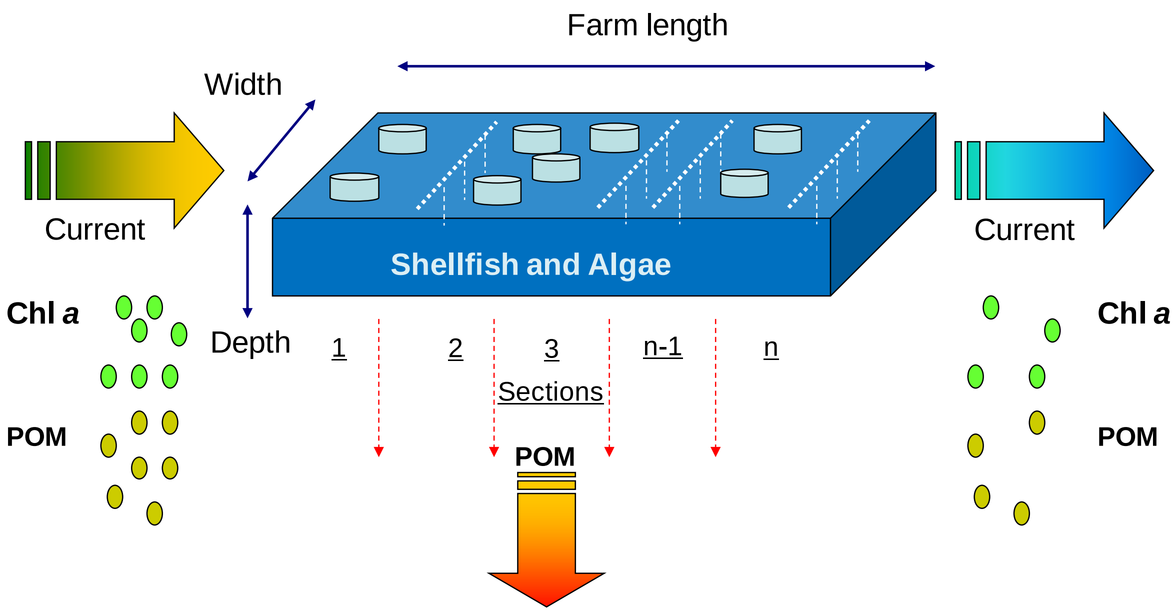

Fig. 1 - Conceptual representation of the FARM model, including options for Integrated Multi-Trophic Aquaculture (IMTA).

FARM (Fig. 1) uses individual growth models to relate shellfish growth to the biogeochemistry 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 *Panopea generosa*, the Pacific oyster *Crassostrea gigas*, the Manila clam *Ruditapes philippinarum*, and the Mediterranean mussel *Mytilus galloprovinciallis*. A net energy balance approach was used, for which several models are currently available (Silva et al. 2011; Grant & Bacher 1998; Hofmann et al. 1995; Kobayashi et al. 1997), and calibration was carried out for local conditions and validated using *in situ* culture practice data. For geoduck, where no physiological growth model is available, equations were drawn from the literature and experimental studies executed by Fisheries and Oceans Canada. The development of an individual growth model for geoduck and its integration in FARM, together with the application of these models to a case study farm in Eld Inlet, SPS, is presented in a separate report. The work presented herein focuses on case studies for the three other shellfish species of importance in the SPS area: Pacific oyster, Manila clam, and Mediterranean mussel.

The main objectives of this work were to:

1. Simulate the production of harvestable biomass at the different test farms with a reasonable degree of accuracy;
2. Determine the bioextraction potential of these test farms, representing the main cultivated bivalves in South Puget Sound.

Methods

The FARM model (Ferreira et al. 2007) simulates 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 and finfish growth models, iv) ASSETS eutrophication screening model (Bricker et al., 2003).

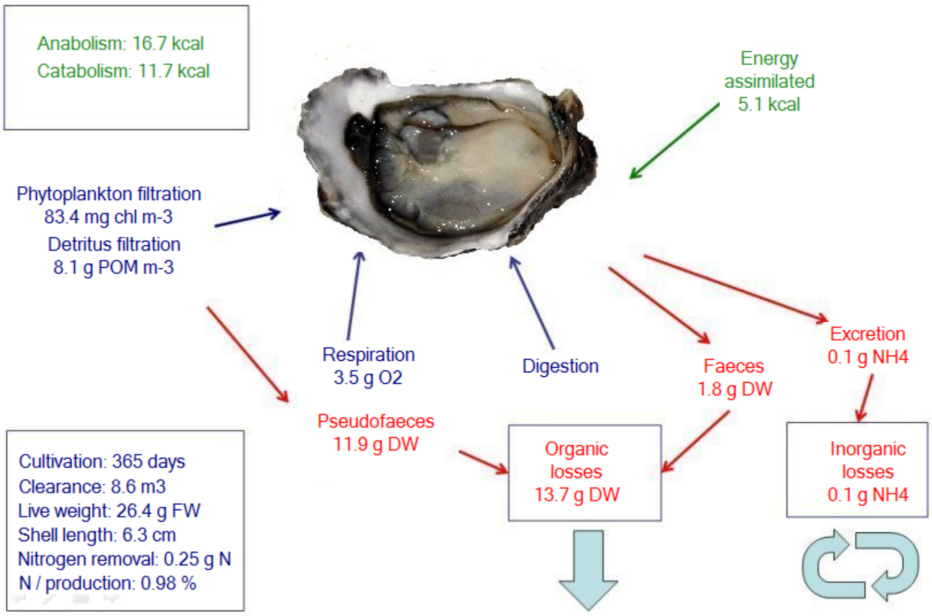

Fig. 2 - Conceptual representation of the FARM model, including options for Integrated Multi-Trophic Aquaculture (IMTA).

Three different types of outputs may be 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.

Table 1 - Case studies used for application of FARM

Species	Location	Notes
Pacific oyster	Eld Inlet	'Chelsea gems', small oysters grown in flip-bags, sold after a short growth period
	Totten Inlet	Larger oysters in bottom culture, with typical grow-out cycle
Manila clam	Eld Inlet	Bottom culture in bags
	Little Skookum	Bottom culture (on bottom)
Mediterranean mussel	Totten Inlet	Deepwater farm – large area (36,783 m^2) of high density suspended raft culture

Existing individual models for Pacific oyster, Manila clam, and Mediterranean mussel (Saurel et al., 2014; Silva et al., 2011) were calibrated for environmental drivers local to the cultivation area. Measured growth drivers were used to run the individual growth models, and the same drivers were used for the FARM model simulations.

Table 2 – Culture practice data used for application of FARM (courtesy of PSI)

Farm Location	**Eld Inlet**	**Totten Inlet**	**Eld Inlet**	**Little Skookum Inlet**	**Totten Inlet**
Farmed Species	**Pacific Oyster**	**Pacific Oyster**	**Manila Clam**	**Manila Clam**	**Mediterranean mussel**
Culture Type	Tumbled Bags	Singles on bottom	Clam bags	On Bottom	Raft suspended
Ploidy	Diploid	Triploid	Diploid	Diploid	Diploid
Width (m)	21.35	30	30.5	53	183
Length (m)	67	150	64	53	201
Area (m2)	1433	4500	1954	2803	36,783
Stocking density (ind m^{-2})	269		249.0	555.6	7,500
Individuals	364750	477,000	450 clams per bag	1,810,500	1,500,000 per raft
Seed weight (g)	0.55	0.55	0.14	0.14	0.002
Harvest weight (g)	36.32	120.00	-	23.30	23.3
Planting period (months)	November	7	10	5	All year
Growout period (days)	365	8	1305	730	11-16
Harvest period (month)	September	1	1.5	3 times/year	All year
Mortality (% over cycle)	2	32	20	10-15	50
Seed cost ($ ind^{-1})	0.048	-	0.004	0.005573	0.004
Harvest value ($ kg^{-1})	16.4	1.9	6.6	6.3	2.5
Total harvest (kg)	545	47,343	3752	105,898.22	1,021,500[1]
Total value ($)	107000	94,605	25860	662,447.04	1,309,584[1]
Annualized gross income ($)	107000	94,605	25860	662,447.04	1,309,584[1]

[1] Value for two farms combined (Gallagher Cove & Deepwater)

As an example of the outputs from the individual models, Fig. 2 shows the calibration of the *Crassostrea gigas* model for 'Chelsea gems', small Pacific oysters grown in Eld Inlet.

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 for the various case studies (Table 1).

A critical requirement for the case studies is a good description of culture practice. This was prepared by PSI on the basis of data reported by the shellfish industry for specific farms (Table 2).

These data were used to set up the FARM model inputs, as exemplified for Mediterranean mussels in Fig. 3.

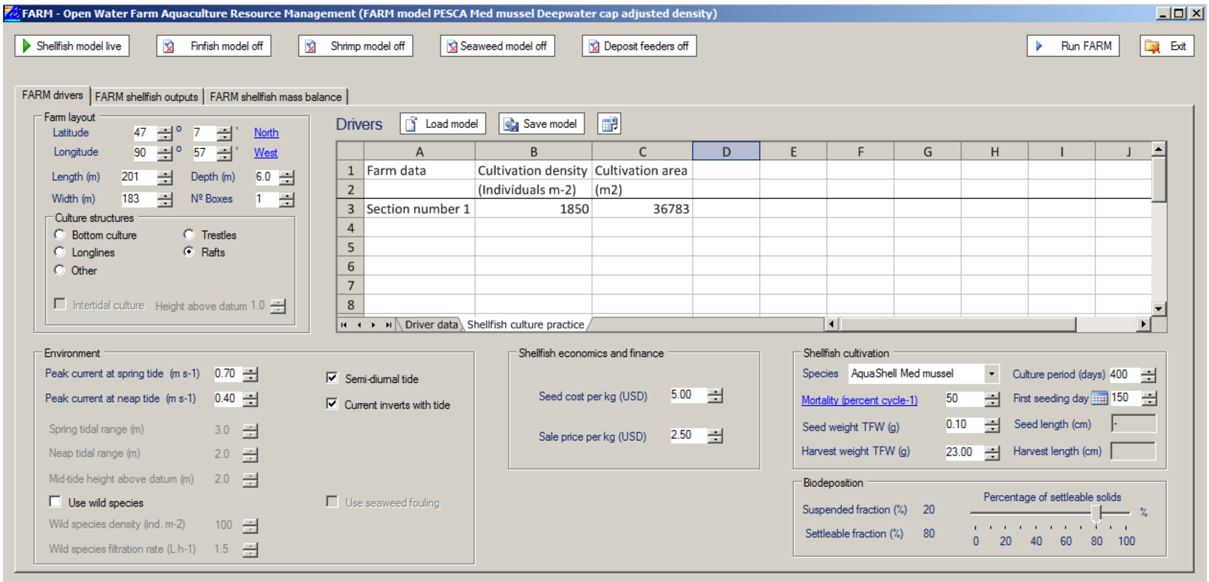

Fig. 3 – Setup of the FARM model for *Mytilus galloprovincialis* raft culture at Deepwater farm in Totten Inlet (see below for explanation of seeding density).

A total of six farm-scale models were set up in FARM, of which results are shown for three species at five locations. As indicated above, the geoduck simulations are presented in a separate report, which describes model conceptualization and implementation, since a completely new model was built to represent this species.

Results and discussion

The set of tables below present the results of the simulations for the three species, using the standard model setup.

Table 3 shows the outputs for Pacific oyster culture at two sites. Both farms show a relatively good match to data. Simulated production for Totten Inlet is lower than the declared harvest, but if the harvest is calculated from Table 2, as H=N*S*W, where N is the number of individuals, S is survival, and W is the unit weight at harvest, the harvestable biomass is 38,287 kg, lower than the declared value of 47,343 kg.

Table 3 – Production and environmental effects of two Pacific oyster farms in SPS (per cycle)

Variable	Eld Inlet	Totten Inlet
Model inputs		
Seeding (kg TFW) per production cycle	800	1000
Model outputs		
Production		
Total (TPP) (kg TFW) per production cycle (declared value in brackets)	23000 (19395)	38723 (47343)
Average Physical Product (APP, Output/Input)	30.4	40.6
Environmental externalities		
Change in percentile 90 NH_4^+ concentration (µmol L	9.02 (in) – 9.01 (out)	9.40 (in) – 9.36 (out)
Change in percentile 90 chlorophyll (mg chl m^{-3})	16.65 (in) – 16.57 (out)	16.24 (in) – 15.99 (out)
Change in percentile 10 O_2 concentration (mg L^{-1})	8.46 (in) – 8.45 (out)	8.43 (in) – 8.44 (out)
ASSETS eutrophication model score	(4) No change (in to out)	(4) No change (in to out)
Profit and loss		
Sales ($ per cycle)	152,000	74,000
Total income ($ per cycle)	152,000	74,000
Seed ($ per cycle)	22,000	27,000
Total marginal expenditure ($ per cycle)	22,000	27,000
Income-Expenditure ($ per cycle)	130,000	46,000
Gross profit ($ per cycle)	130,000	46,000

The value obtained in FARM falls somewhere in the middle of the two. Culture practice varies with farm, growth cycle, and economic conditions, and it is not an exact science. What FARM aims to do is reproduce general patterns of growth and environmental externalities, which is does successfully for Pacific oyster culture.

It is worth noting that the environmental externalities are inconsistent when considering the input and output concentrations; this is a model artefact which occurs in some simulations due to the bidirectional tidal simulation, when very small changes exist. These small changes will only affect the ASSETS eutrophication score in exceptional circumstances.

The role of the Totten Inlet oyster farm in nutrient removal is shown in Fig. 4, which represents the annualized mass balance of the culture. There is a net removal of 265 kg of nitrogen, which equate to 0.7% of the total live weight biomass produced.

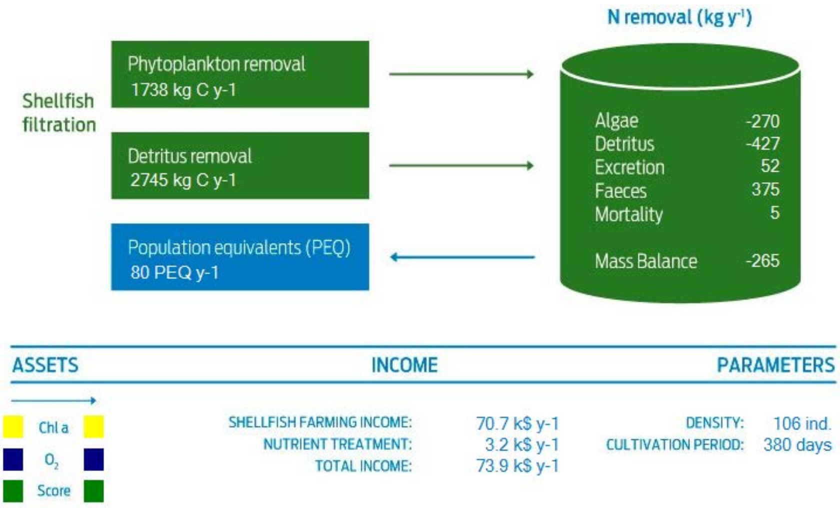

Fig. 4 – Mass balance for bottom culture of Pacific oysters in Totten Inlet.

Table 4 shows the equivalent FARM model outputs for Manila clam farms in Eld Inlet and Little Skookum. In both cases the Total Physical Product (TPP), i.e. the harvestable biomass produced over a culture cycle, are a reasonable match to the declared production.

Table 4 – Production and environmental effects of two Manila clam farms in SPS (per cycle)

Variable	Eld Inlet	Little Skookum
Model inputs		
Seeding (kg TFW) per production cycle	100	400
Model outputs		
Production		
Total (TPP) (kg TFW) per production cycle (declared value in brackets)	3450 (3752)	18485 (20911)
Average Physical Product (APP, Output/Input)	35.5	50.9
Environmental externalities		
Change in percentile 90 NH_4^+ concentration (µmol L	8.88 (in) – 8.88 (out)	8.88 (in) – 8.87 (out)
Change in percentile 90 chlorophyll (mg chl m^{-3})	15.08 (in) – 15.03 (out)	15.08 (in) – 14.95 (out)
Change in percentile 10 O_2 concentration (mg L^{-1})	8.50 (in) – 8.49 (out)	8.51 (in) – 8.49 (out)
ASSETS eutrophication model score	(4) No change (in to out)	(4) No change (in to out)
Profit and loss		
Sales ($ per cycle)	23,000	122,000
Total income ($ per cycle)	23,000	122,000
Seed ($ per cycle)	3,000	14,000
Total marginal expenditure ($ per cycle)	3,000	14,000
Income-Expenditure ($ per cycle)	20,000	108,000
Gross profit ($ per cycle)	20,000	108,000

As in the case of the two oyster farms, there are no detectable changes in terms of environmental externalities, although the chlorophyll percentile 90 is a little lower due to shellfish filtration.

As in the previous case, only a mass balance analysis (Table 6) will allow a quantification of ecosystem services, since the relatively low bivalve stocking densities and high chlorophyll values over parts of the year mean that there is not a clear phytoplankton drawdown.

Table 5 shows FARM results for a completely different situation, a large Mediterranean mussel farm in Totten Inlet. Both the area and the stocking density are an order of magnitude higher than the oyster and clam farms, and this is reflected in the food depletion simulations. From Table 2, the calculated harvestable biomass, using H=N*S*W, as above, is 3,217,723 kg for Deepwater, against a declared harvest of 814,768 kg, calculated from the declared total harvest and area proportions of the two sites (see footnote in Table 2).

We assume the density per square meter is for the rafts themselves, and have adjusted this to reflect the difference in the two harvests above—a nominal *overall* density of 1850 ind. m^{-2} (~7500/4 ind. m^{-2}) was used for the standard run.

Table 5 – Production and environmental effects of a Mediterranean mussel farm in SPS (per cycle)

Variable	Totten Inlet
Model inputs	
Seeding (kg TFW) per production cycle	34000
Model outputs	
Production	
Total (TPP) (kg TFW) per production cycle (declared value in brackets)	868570 (814768)
Average Physical Product (APP, Output/Input)	25.5
Environmental externalities	
Change in percentile 90 NH_4^+ concentration (µmol L	8.92 (in) – 9.00 (out)
Change in percentile 90 chlorophyll (mg chl m^{-3})	15.60 (in) – 13.72 (out)
Change in percentile 10 O_2 concentration (mg L^{-1})	8.50 (in) – 8.40 (out)
ASSETS eutrophication model score	(4) No change (in to out)
Profit and loss	
Sales ($ per cycle)	2171,000
Total income ($ per cycle)	2171,000
Seed ($ per cycle)	170,000
Total marginal expenditure ($ per cycle)	170,000
Income-Expenditure ($ per cycle)	2001,000
Gross profit ($ per cycle)	2001,000

FARM indicates a significant reduction in chlorophyll of over 12%, which means that the Deepwater farm plays an important role in mitigating eutrophication conditions.

Table 6 – Positive 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

In this situation, the simulated change in ammonia and dissolved oxygen is correctly simulated, and the results suggest that the negative externalities of mussel culture are relatively small for both variables.

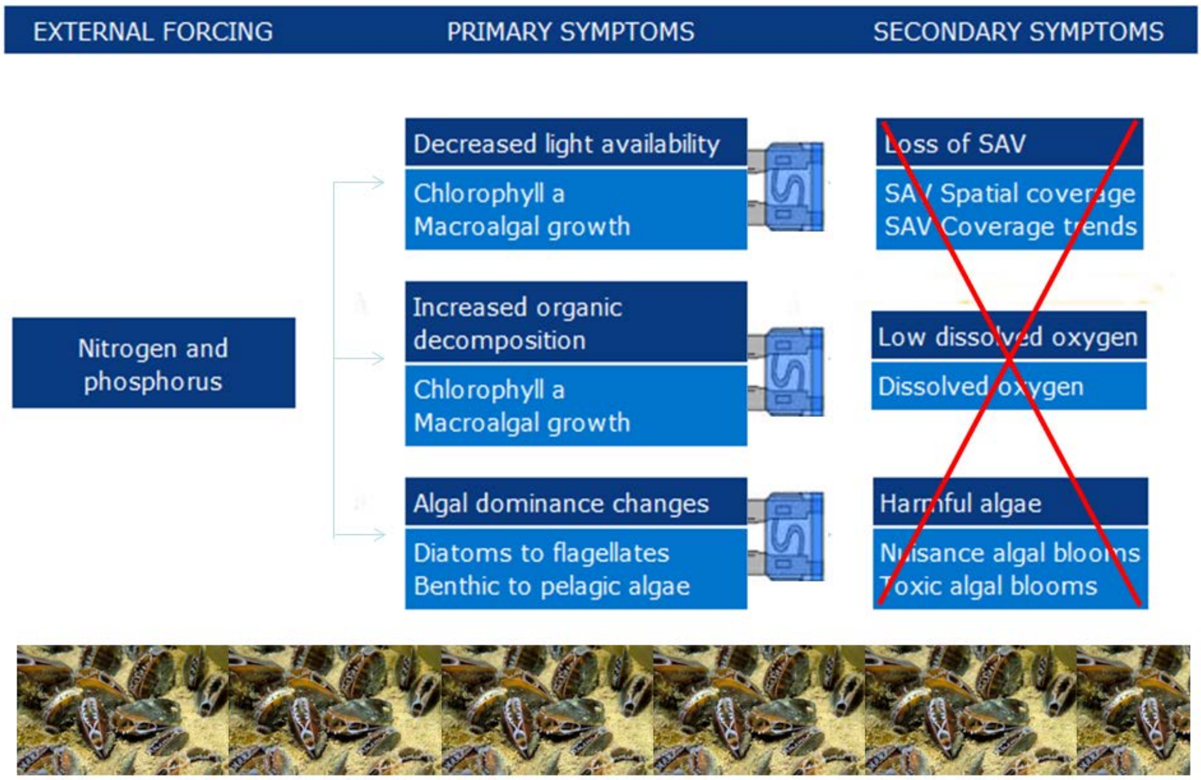

Fig. 5 – The role of mussels (and other bivalves) in short-circuiting the organic decomposition cycle.

In the case of dissolved oxygen, the small (<5 mg L^{-1}) reduction is insignificant when compared to the large positive role of short-circuiting the organic decomposition cycle of phytoplankton (see e.g. Bricker et al., 2003), and preventing the resulting oxygen drawdown (Fig. 5).

An assessment of the role of the three species of bivalves in mitigating eutrophication is given in Table 6, and these numbers can be combined with simulations executed for Manila clam in North Puget Sound (Saurel et al., 2014), and geoducks in SPS (PESCA project), to evaluate the role of bivalve culture in Puget Sound in top-down control of eutrophication symptoms.

In addition, this approach can be extended to other areas of the United States to include similar estimates made for the Eastern oyster *Crassostrea virginica*, which will for the first time allow a budget to be made of the role of bivalve shellfish in controlling eutrophication at a national scale.

Table 7 – Scaling of shellfish ecosystem services to all of Puget Sound (adapted and extended from Washington Sea Grant, 2015).

Shellfish species	Live weight harvested		Provisioning services	Unit price	Net nitrogen removal	Regulatory services	Total value
	(lb)	(tonnes)	(USD)	(USD/kg)	(tonnes)	(USD)	(USD)
Mussels	3,655,551	1,660	7,940,408	4.78	81.46	987,340	8,927,748
Geoduck clam	1,613,114	732	24,482,209	33.43	6.10*	73,939	24,556,148
Manila clam	7,259,401	3,296	17,451,985	5.30	161.50	1,957,575	19,409,560
Pacific oyster	8,793,138	3,992	34,853,940	8.73	28.99	351,350	35,205,290
Soft shell clam	1,419,509	644	454,198	0.70			454,198
Other	664,905	302	6,738,647	22.32			6,738,647
Total	23,405,618	10,626	91,921,390		278.04	3,370,204	95,291,594

* Nitrogen removal from Cubillo et al., 2015.

Table 7 shows the application of the FARM model outputs to Puget Sound. Geoducks were included using outputs of the FARM application by Cubillo et al. (2015) to Chelsea Farms, Eld Inlet, and the overall value of both provisioning services (goods) and regulatory services for eutrophication control were calculated for the Sound.

The potential value of eutrophication abatement, evaluated as nitrogen removal, is of the order of three million dollars per year. This is equivalent to 3.5% of the total ecosystem services considered, but the farmgate unit price for shellfish (column 5) seems excessive for some species, in particular for mussels and Manila clams. Furthermore, there are no data for N removal by soft shell clams, and no breakdown of ‘other’ into component species, which means that if we consider only the shellfish species production for which both provisioning and regulatory services are determined, eutrophication abatement increases to 4% of the total.

Detailed aquaculture data on a national scale are not readily available—the most useful source is the NOAA-NMFS (2015) report on the fisheries of the United States (National Marine Fisheries Service, 2015), which only breaks down shellfish aquaculture into clams, mussels, and oysters. Since these broad groups include blue mussel (East Coast) and Mediterranean mussel (West Coast), and similar divisions into Eastern oyster/Pacific oyster, and quahogs/Manila clams, it is impossible to extrapolate regulatory services for the US with any certainty.

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