



Ecosystem services of geoduck farming in South Puget Sound, USA: a modeling analysis

Alhambra Martínez Cubillo¹  · João Gomes Ferreira² · Christopher Michael Pearce³ · Robert Marshall⁴ · Dan Cheney⁵ · Bobbi Hudson⁵

Received: 25 October 2017 / Accepted: 30 July 2018 / Published online: 23 August 2018
© Springer Nature Switzerland AG 2018

Abstract

Provisioning and regulatory ecosystem services of Pacific geoduck clam (*Panopea generosa*) culture were simulated for an intertidal shellfish farm in Eld Inlet, South Puget Sound, Washington, USA. An individual geoduck clam growth model was developed, based on a well-established framework for modeling bivalve growth and environmental effects (AquaShell™). Geoduck growth performance was then validated and calibrated for the commercial farm. The individual model was incorporated into the Farm Aquaculture Resource Management (FARM) model to simulate the production cycle, economic performance, and environmental effects of intertidal geoduck culture. Both the individual and farm-scale models were implemented using object-oriented programming. The FARM model was then used to evaluate the test farm with respect to its role in reducing eutrophication symptoms, by 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). At the current culture density of 21 ind m⁻², geoduck farming at the Eld Inlet farm (area: 2684 m²) provides an annual ecosystem service corresponding to 45 Population-Equivalents (PEQ, i.e. loading from humans or equivalent loading from agriculture or industry) in top-down control of eutrophication symptoms. This represents a potential nutrient-credit trading value of over USD 1850 per year, which would add 1.48% to the annual profit (USD 124,900) from the clam sales (i.e. the provisioning service). A scaling exercise applied to the whole of Puget Sound estimated that cultured geoducks provide a significant ecosystem service, of the order of 11,462 PEQ per year (about USD 470,600) in removing primary symptoms of eutrophication, at the level of the whole water body. The modeling tools applied in this study can be used to address both the positive and negative externalities/impacts of shellfish aquaculture practices in the ecosystem and thus the trade-offs of the activity.

Keywords Aquaculture · Carrying capacity · Ecosystem services · FARM model · Geoduck · *Panopea generosa* · Puget sound · Shellfish farming

✉ Alhambra Martínez Cubillo
alhambra.cubillo@longline.co.uk

Introduction

The USA imported 91% of the aquatic products it consumed in 2013, up from 86% in 2012 (Tiller et al. 2013), corresponding to a trade deficit of USD 11.2 billion (NOAA 2017). At present, there is a substantial effort to promote shellfish cultivation in the USA, including the National Oceanic and Atmospheric Administration (NOAA) aquaculture policy (NOAA 2011a), which covers both the National Shellfish Initiative (NOAA 2011b) as well as the aquaculture component of the National Ocean Policy (NOAA 2016). These policies and initiatives are meant to increase USA aquaculture production with the goal of reducing this substantial trade deficit.

Shellfish aquaculture, however, often faces significant opposition from environmental non-governmental organizations and the general public due to a variety of concerns including ecological carrying capacity, organic enrichment, visual/noise pollution, and plastic debris/microplastics (Giles 2006; Mallet et al. 2006; Zhou et al. 2006; Nizzoli et al. 2011). But shellfish farms can also have a number of positive impacts on the local environment such as creation of habitat for other organisms (Powers et al. 2007; McDonald et al. 2015) and filtering/cleaning the water column (Newell 2004; Lindahl et al. 2005; Zhou et al. 2006). The positive and negative ecological impacts of shellfish culture are often difficult to measure directly, since cultivation generally takes place in highly variable environments, which hinder an objective analysis of the trade-offs of the activity.

Development of shellfish farming in the USA focuses on both volume and niche-market products, the latter representing high-value species with significant export potential which can help redress the trade deficit—the Pacific geoduck clam (*Panopea generosa*; Gould, 1850) being a prime example. The Pacific geoduck inhabits intertidal and subtidal sand substrata along the northwest coast of North America from Alaska to Baja California (Bernard 1983), primarily Alaska, Washington (USA), and British Columbia (Canada). This bivalve mollusk is the largest infaunal clam in the world, reaching an average weight of 0.68 kg (1.5 pounds) at maturity, with specimens over 3 kg (6.6 pounds) having been recorded (Goodwin and Pease 1987). Geoducks are among the longest-lived organisms in the animal kingdom, with an average reproductive lifespan of 30 years (Sloan and Robinson 1984), and the oldest recorded specimen being 168 years old [although individuals over 100 years old are rare (Orensanz et al. 2004)]. The longevity and phallic shape of the geoduck are some of the characteristics that make it a preferred species in the Chinese market, where it can reach a price of USD 20–40 kg⁻¹ landed value (Washington Sea Grant 2015) or USD 100–300 kg⁻¹ in Chinese restaurants.

The geoduck's high market value has created a rapidly developing fishing/aquaculture industry, with harvesting in the states of Alaska, Washington, and Oregon (USA) and the province of British Columbia (Canada). Aquaculture of geoducks has been on a commercial scale since the mid-1990s (Brown and Thuesen 2011), but due to the geoduck's market demand, mainly from Asian countries, production began to increase in 2000 and has maintained a mostly upward trajectory in Washington (Washington Sea Grant 2015). In 2013, Washington produced about 732,000 kg (1,613,114 pounds) of cultured clams, accounting for 7% of total aquaculture production in weight and 27% of total value for the state (Washington Sea Grant 2015). By comparison, the Pacific oyster, the main cultivated species, accounted for 38% of total production and total value of Washington cultured shellfish species. Regionally, in South Puget Sound in 2013, the Manila clam was the primary cultured species in terms of landings (42%) but accounted for only 16% of total value, while cultured geoduck clams accounted for only 18% of total production (713.6 t or 1,573,169 pounds) but contributed 44%

of the regional value (US\$23,648,591) (Washington Sea Grant 2015). In addition to cultured product, there is a substantial wild harvest of geoduck clams in South Puget Sound. According to Washington Department of Fish and Wildlife catch records, in 2013, the wild geoduck harvest totalled 217.6 metric tons (479,739 pounds), valued at US\$3.6 million.

Cultured geoducks are hatchery-produced and deployed as seed for grow-out in intertidal and subtidal beds (e.g., in tidelands in Puget Sound) until harvest 5–7 years later. Intertidally, the seeds are grown in PVC tubes that are sunk into the substrate and covered in netting (for predator-protection). In Washington, approximately 140 ha is currently exclusively used for intertidal geoduck culture, there being plans for significant expansion in the near future (Vadopalas et al. 2015). This increasing interest in geoduck farming in recent years has become the subject of controversy, with some stakeholders claiming that geoduck farming has negative impacts on marine ecosystems, including negative effects on surrounding organisms and eelgrass, visual pollution due to predator-protection tubes and netting in cultivation areas, debris due to loss of equipment, and noise due to harvesting activities. Recent research in both British Columbia and Washington suggest that the negative impact of geoduck culture and harvesting on local infauna, epifauna, substrate characteristics, and eelgrass is minimal and likely less than that due to natural seasonal fluctuation (Liu et al. 2015; McDonald et al. 2015; VanBlaricom et al. 2015). Visual impacts of geoduck farming are greatest at the nursery stage, due to use of the predator-protection tubes during the first 2 years of growth, but these are only visible for an estimated 2% of the time over the 6-year growth cycle (D. Cheney, pers. obs.). The use of large single nets over the tubes (as opposed to individual mesh tops on each tube) has substantially reduced debris, and farmers have addressed the noise issue by using water-cooled diesel pumps with appropriate sound-absorbing housing, deployed in boats offshore (D. Cheney, pers. obs.).

This creates a need for an objective evaluation of the ecological role of farmed geoducks in the surrounding ecosystem, including removal of natural seston due to their filter feeding, thus cleaning the water (i.e., drawdown of phytoplankton and detritus) and return of organic (faeces and pseudofaeces) and inorganic (excretory) products.

The main objectives of the present study were to (1) develop and validate an individual growth model to simulate production and environmental effects of Pacific geoduck culture; (2) integrate this individual model into the well-tested Farm Aquaculture Resource Management (FARM) model to simulate a typical production cycle for a Pacific geoduck clam farm in South Puget Sound; and (3) apply the FARM model to predict the potential production and ecological carrying capacities of the farm and use the model outputs to analyze the role of geoduck culture in Puget Sound as a whole.

Materials and methods

Study site and culture practices

This study used Chelsea Farms (Washington) as a demonstration case. The company farms Manila clams, Pacific oysters, and geoducks and has 20.23 ha (50 acres) of intertidal beach area with farms in five different inlets in South Puget Sound, particularly Eld Inlet and Totten Inlet. Our model was calibrated for the Eld Inlet farm, located in the southwest part of Puget Sound (Fig. 1), where geoduck clams are manually planted on intertidal beds inside PVC tubes covered with a protective mesh to prevent predation. The PVC tubes are about 10–15 cm (4–

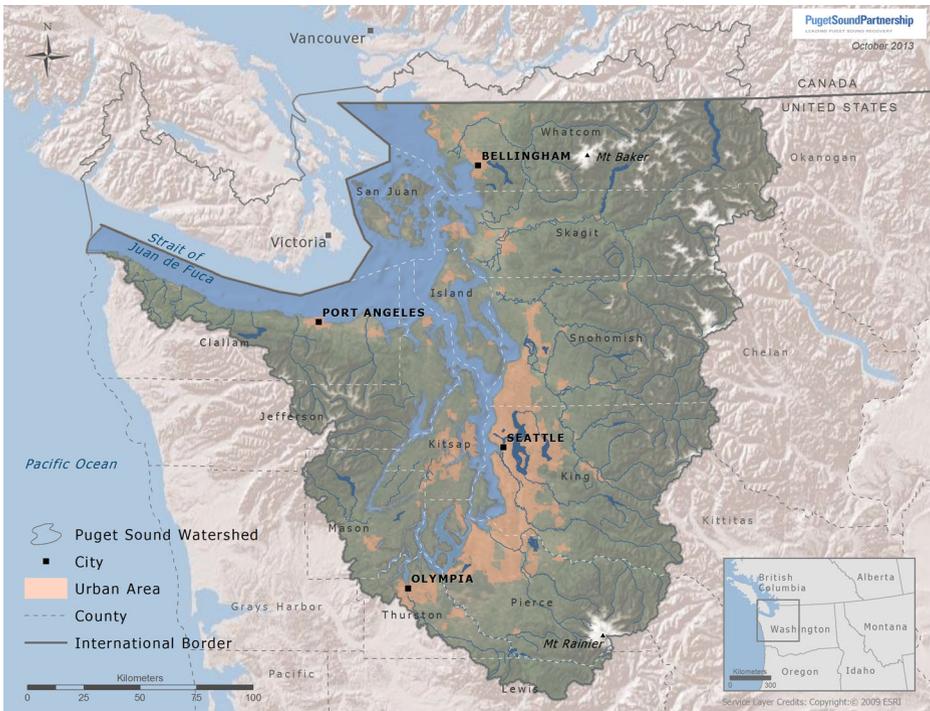


Fig. 1 Location (red cross) of Chelsea Farms in Eld Inlet (South Puget Sound, Washington, USA)

6 in) in diameter and are placed in rows approximately 50 cm apart from each other (i.e., 2.5 tubes m^{-1} or 7.5 tubes m^{-2}), as shown in Fig. 2. The animals are supplied by commercial hatcheries and harvested during the fifth year after seeding. The shellfish are cultivated as five separate year classes in different sections of the farm, allowing for an annual harvest. As a consequence, approximately one fifth of the total area is harvested every year and subsequently re-seeded. The detailed farm culture practice is given in Table 1 and Fig. 2.

Geoduck individual growth model

An individual Net Energy Balance (NEB) model for geoduck clams was developed, based on the generic AquaShell™ framework for bivalves (e.g., Ferreira et al. 2012) to simulate the physiology, growth, and environmental effects of geoducks. The individual model was tested in WinShell, a user-friendly platform to handle input and output from AquaShell™ that generates overall mass balance calculations for the whole culture cycle, taking into account both production and environmental variables.

Data on physiology and growth performance were obtained from the literature and were parameterized for the study site. Functions for key physiological processes specific to geoducks follow Marshall (2012), Marshall et al. (2014a, b), and unpublished data (C.M. Pearce, Fisheries and Oceans Canada). Formulations for morphometric relationships were obtained from Bureau et al. (2002, 2003), Gribben and Creese (2005), García-Esquivel et al. (2013), and Vadopalas et al. (2015).

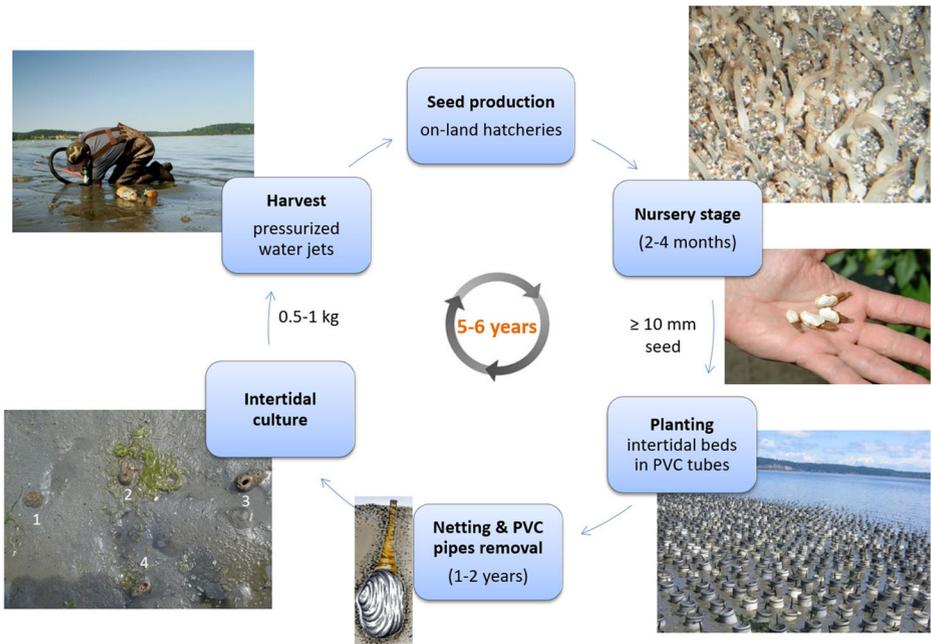


Fig. 2 Stages of geoduck clam (*Panopea generosa*) culture in Puget Sound. White numbers 1–4 show exposed siphons or little depressions in the sand, a sign that clams are burrowed below

The model was calibrated and validated using literature growth data from British Columbia and Puget Sound (Hoffmann et al. 2000; Bureau et al. 2003; Campbell and Ming 2003) and data from growth monitoring by Chelsea Farms.

Table 1 Culture practice, environmental details, and finance variables for Chelsea Farms (Eld Inlet, South Puget Sound, Washington, USA)

Descriptor	Detail
Location	47°07' N, 122°57' W
Size and layout	2684 m ² on strips for 5 different year classes (annual rotation) Intertidal; 3-m water depth; length 122 m; width 22 m
Culture practice	Bottom culture in PVC pipes covered by plastic nets
Seed	Seeding day 180; Culture cycle 1825 days (~5 years) Number of seed planted 55,700; seed density 21 ind. m ⁻² (4 ind. per PVC pipe) Seed weight 2 g
Harvest	Standard harvest weight 562 g total wet weight
Mortality	46% over cycle
Environment	Semi-diurnal tidal cycle Current speeds generated by peak spring and neap tides 0.7 and 0.4 m s ⁻¹ , respectively Spring and neap tidal range 4 and 2.5 m, respectively
Water quality	Salinity, temperature, chlorophyll, detritus, and total particulate matter (TPM) for Eld Inlet (see Table 2)
Finance	Seed cost: US\$0.5 ind. ⁻¹ Farm-gate sale price: US\$43.5 kg ⁻¹ Annual yield: 3465 kg total wet weight Annualized gross income: US\$145,182

The model simulates changes in individual weight and shell length and is driven by size-allometric equations and relevant environmental variables (Table 2). Clearance rate (CR) is a function of allometry (CR_m), chlorophyll *a* (CR_{chl}), salinity (CR_s), and water temperature (CR_t) (Eqs. 1–3). Due to the absence of a specific equation for geoducks, the allometric relationship for Pacific oysters (Eq. 7 in Kobayashi et al. 1997) was calibrated to fit the geoduck clearance rates obtained in laboratory experiments (Robert Marshall, unpublished data) by means of a weighting factor:

$$\text{Weighting Factor} = 2.51 \times \left(\frac{DW}{DW_{st}} \right)^{0.279} \tag{1}$$

$$CR_m = \frac{1}{\text{Weighting Factor}} \tag{2}$$

where CR_m is the clearance rate ($L\ gDW^{-1}\ h^{-1}$) as a function of individual soft-tissue dry weight (DW) and DW_{st} is the standard dry-tissue weight of 107.04 g, at which the clearance rate was determined.

This clearance rate as a function of individual weight (CR_m) was used to model the effect of chlorophyll *a* concentration following a cubic polynomial equation, after Marshall et al. (2014b):
if $[Chl] < Chl_t$;

$$CR_{chl} = \frac{CR - Chl_t}{DW_{st}} \tag{3}$$

if $[Chl] > Chl_t$;

Table 2 Data used to run the geoduck clam (*Panopea generosa*) AquaShell™ individual model and the FARM model for simulation of farm-scale production and environmental effects, according to Chelsea Farms' culture practice

Julian day	Temperature (°C)	Salinity	Chlorophyll <i>a</i> (ug L ⁻¹)	POM (mg L ⁻¹)	TPM (mg L ⁻¹)	DO ^a (mg L ⁻¹)	DIN ^a (μmol L ⁻¹)
10	7.47	27.84	2.0			8.4	
33	7.77	26.91	2.1			8.8	
61	6.53	26.05	0.9			9.8	
102	9.74	26.29	1.1			11.4	
130	11.20	27.00	4.0			13.7	
165							2
167	16.59	26.78	5.5	2.563	8.045	14.0	
187	14.88	28.12	3.6	2.812	7.533	13.1	
210							4
220	16.23	28.38	14.5	1.723	4.281	14.1	
240							7
255	16.67	28.74	15.1			11.6	
270							5
285	13.60	28.91	14.3	2.659	14.739	8.4	
306	11.51	28.73	28.4			12.5	
330							10
348	7.97	28.11	1.5	1.316	4.130	7.7	

POM particulate organic matter, TPM total particulate matter, DO dissolved oxygen, DIN dissolved inorganic nitrogen

^a The last two columns are used only in the FARM model

$$CR_{chl} = CR_m \times (0.0323 + 0.012 \text{ Chl} - 4.3 \times 10^{-4} \text{ Chl}^2 + 3.7 \times 10^{-6} \text{ Chl}^3) \times C \quad (4)$$

where CR_{chl} is the CR as a function of chlorophyll a ($L \text{ gDW}^{-1} \text{ h}^{-1}$), Chl_t is the chlorophyll threshold of $4.8 \mu\text{g L}^{-1}$ (the lowest $Chl a$ concentration tested in the laboratory), C is a correction factor of 0.5, and $CR-Chl_t$ is the experimental CR obtained at the chlorophyll threshold, which is $7.8 \text{ L clam}^{-1} \text{ h}^{-1}$. We assumed that this clearance rate is maintained constant at chlorophyll concentrations $< 4.8 \mu\text{g L}^{-1}$.

The effect of water temperature (T , $^{\circ}\text{C}$) on the clearance rate (CR_t , $L \text{ gDW}^{-1} \text{ h}^{-1}$) was modeled as a Gaussian curve when CR is above or below the optimal temperature (T_{opt}) of 15°C :

$$CR_t = CR_{chl} \frac{T}{T_{opt}} e^{\left(1 - \frac{T}{T_{opt}}\right)} \quad (5)$$

The effect of salinity (S , psu) on the clearance rate (CR_s , $L \text{ gDW}^{-1} \text{ h}^{-1}$) was modeled considering an optimal salinity around 32–33 psu (C.M. Pearce, unpublished data):

if $S < S_{min}$:

$$CR_s = 0 \quad (6)$$

if $S_{max} > S \geq S_{min}$:

$$CR_s = CR_t \frac{(S - S_{min})}{(S_{max} - S_{min})} \quad (7)$$

where at salinities below $S_{min} = 20$ psu, the animal stops filtering and above $S_{max} = 29$ psu, there is no restriction of the CR due to salinity. Marshall (2012) found that clams held at salinities of 17 and 20 psu had significantly lower CRs and higher mortality rates than those held at salinities of 24 and 29 psu.

Filtration rate (FR , $\text{mgDW ind}^{-1} \text{ day}^{-1}$) is then estimated as the product of CR ($L \text{ ind}^{-1} \text{ day}^{-1}$) and the concentration of phytoplankton and detritus in the seawater. Ingestion rate is limited through pre-ingestive rejection of particulate material as pseudofeces to prevent overloading of the filtration apparatus. Production of pseudofeces is estimated as a function of seston concentration following Grant and Bacher (1998). The threshold for pseudofeces production was considered to be 5 mg L^{-1} (Bayne and Worrall 1980). Most of the food entering the gut is assimilated by the organism, the rest being eliminated as faeces. Based on data for other bivalve species (Ren et al. 2006; Bayne 2017), a constant assimilation efficiency of 70% was used, although it should be noted that this value is variable over different timescales, diets, and different life stages (Ren et al. 2006; Bayne 2017).

The energy contents of phytoplankton and detrital particulate organic matter were taken to be 23.5 (Chattopadhyay 2014) and 5 J mg^{-1} (Tenore 1981; Palavesam et al. 2005), respectively. The energy available for geoduck growth and reproduction (EA , $\text{J ind}^{-1} \text{ day}^{-1}$) was calculated as the difference between the energy obtained from food (anabolism, A) and the energy spent in catabolic processes (C):

$$C = C_{fa} + C_{fe} \quad (8)$$

$$EA = A - C \quad (9)$$

where catabolism is divided in fasting catabolism (C_{fa}) and feeding catabolism (C_{fe}), both in $J \text{ ind}^{-1} \text{ day}^{-1}$.

Oxygen consumption rate (OCR, $\text{mg O}_2 \text{ gDW}^{-1} \text{ h}^{-1}$) scales significantly with both salinity and animal size (Marshall 2012). Significantly lower oxygen consumption was found in clams at a salinity of 29 compared to 17, 20, and 24 psu. Clams held at salinities of 17 and 20 exhibited erratic pumping behavior, characterized by frequent starts and stops and closure of siphon tips, which led to higher mortality rates (Marshall 2012). Both salinity and allometry were included to simulate fasting catabolism ($J \text{ ind}^{-1} \text{ day}^{-1}$):

$$OCR = 0.4482 - 0.0055S - 0.0020W \quad (10)$$

$$C_{fa} = OCR \times RC \times DW \times 24 \quad (11)$$

where RC is the respiration cost = $10 J \text{ mg}^{-1} \text{ O}_2$, calibrated from the $14 J \text{ mg}^{-1} \text{ O}_2$ value used for the energy consumed by the respiration of 1 mg of oxygen in other shellfish models (Tušnik 1985; Navarro et al. 1991; Hawkins et al. 2002) and DW is soft-tissue dry weight (g). The effect of temperature on oxygen consumption was not included in the model due to lack of experimental data. Further experimental work on this matter will be needed for geoduck clams in order to improve the present modeling approach.

The energy spent in the feeding process (C_{fe} , $J \text{ ind}^{-1} \text{ day}^{-1}$) was estimated as a fixed proportion of the energy absorbed:

$$C_{fe} = \alpha A \quad (12)$$

Based on data in Widdows and Hawkins (1989), Willows calculated that feeding costs are < 2% at high ingestion rate, increasing to approximately 7% of the absorbed ration at the lowest observed ingestion rate. Since no estimate of the energy spent by geoduck clams in the feeding process was available, this value was calibrated to $\alpha = 0.10$. The energy available for geoduck growth was converted to biomass using a tissue energy content of $20,500 J \text{ g DW}^{-1}$ and a 70% water content of soft tissue (Marshall et al. 2012; García-Esquivel et al. 2013). Similarly, an energy content of $1000 J \text{ g}^{-1}$ and a water content of 19% was used for the shell. The proportion of absorbed energy allocated to growth of soft tissues and shell was calibrated based on the relationship between shell and soft-tissue weight given by Marshall (2012).

Geoduck shell length (SL, mm) was calculated from the total live weight (B, g) based on *P. generosa* experimental data from British Columbia (Bureau et al. 2002):

$$SL = 8.5923 B^{0.4088} \quad (13)$$

The gonad wet weight (GW, g) was calculated from the SL (mm) following Vadopalas et al. (2015):

$$GW = 3 \times 10^{-8} \times SL^{4.2973} \quad (14)$$

According to Andersen (1971) and Campbell and Ming (2003), the minimum reproductive size was set at 37.7 g tissue dry weight. July 1 was considered as the first spawning day, following Andersen (1971), Campbell and Ming (2003), and Vadopalas et al. (2015), and a minimum temperature for spawning of 11.5 °C was used (Sloan and Robinson 1984).

Table 2 shows the environmental drivers obtained through field measurements at the Eld Inlet farm; these were used for individual model runs and subsequently for simulations at the

farm scale. The individual model for geoduck clams was implemented, calibrated, and validated in the InsightMaker™ visual modeling platform and subsequently ported to C++. Mass balance outputs were verified to check consistency across both versions.

Farm-scale population model

The geoduck individual growth model was integrated into the FARM model for projection of geoduck production, economic performance, and environmental effects at the farm scale, using the Eld Inlet environmental drivers and culture practice of Chelsea Farms in South Puget Sound as a case study (Tables 1 and 2). Outputs from this model, together with South Puget Sound water quality and socio-economic data, were combined to provide information about the ecosystem services rendered by geoducks, using the FARM outputs for production (harvestable biomass or total physical product, TPP), return on investment (using the average physical product or APP as a proxy), income, expenditure, gross profit, dissolved nutrient release, and eutrophication assessment.

A marginal analysis to determine the optimal stocking density was obtained by simulating the potential harvest of different stocking densities of geoducks, with the known values for input (US\$0.5 per individual geoduck seed) and output (US\$43.5 per kg) costs. The value of marginal product (VMP) was then used to calculate the marginal physical product (MPP) which corresponds to the first derivative of the TPP curve and yields the point at which profit maximization occurs (Jolly and Clonts 1993; Ferreira et al. 2007, 2011). Finally, the FARM model outputs were scaled to estimate the ecosystem services provided by geoducks for the whole of Puget Sound and to provide an overview of the role of these organisms in the context of the three axes of people, planet, and profit.

Results and discussion

The results generated by the geoduck clam individual growth model together with the mass balance over a culture cycle are briefly reviewed, followed by the FARM modeling results. Finally, a scaling exercise of the services provided by farmed geoducks for the whole of Puget Sound is presented.

Individual geoduck growth model

Figure 3 shows the simulated growth in shell length, tissue wet weight, and total wet weight for a single Pacific geoduck with the Eld Inlet environmental drivers. The individual model reproduced the weight increase in the growing season (mid-June to mid-November) and the negative scope for growth reported during winter. The model predicted a final shell length of 111 mm, a total live weight of 520 g, and a tissue wet weight of 392 g after a 5-year culture cycle. This is in agreement with field and literature data on growth rates, which indicate that geoducks grow about 25 mm in shell length per year, and the model matches the commercial end-point reasonably well (geoducks reach nearly 500–600 g total wet weight in 5–6 years in Puget Sound). Figure 4 shows that the modeled growth curve fits well within the range delimited by the minimum (Hoffmann et al. 2000) and maximum (Bureau et al. 2002) growth curves found in the literature for *P. generosa* for a 5-year growth cycle.

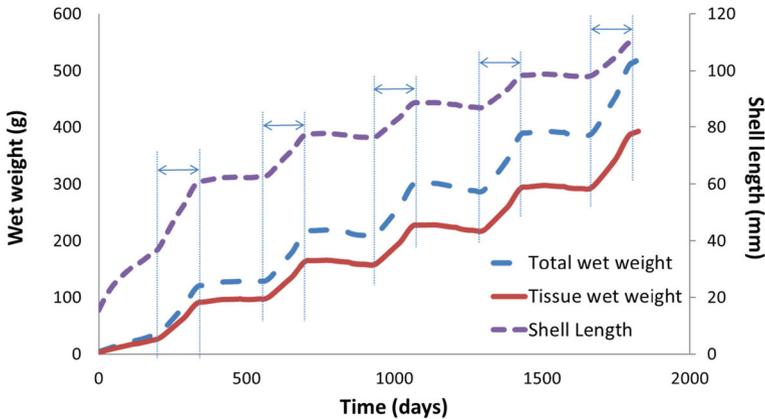


Fig. 3 Simulation of geoduck clam (*Panopea generosa*) individual growth with Eld Inlet environmental drivers. The blue arrows show the periods of growth

The individual model was tested in WinShell. Figure 5 shows the mass balance for cultivation of a geoduck to a market size for the standard density scenario (21 ind m⁻²). Simulation of geoduck growth using Eld Inlet drivers provides outputs on production and environmental effects, such as the mass of phytoplankton or detritus removed from the environment, the faeces and pseudofaeces produced, or the ammonia excreted. During the whole culture cycle, each clam cleared nearly 400 m³ (i.e., an average clearance rate of 9 L h⁻¹) of seawater, consumed 0.73 kg of oxygen, and removed over 20 g of nitrogen, 3.7% of the live weight produced (Fig. 5). Over 73% of the energy uptake was lost in catabolic processes and 27% was assimilated. A single geoduck clam removes 845 g of suspended organic matter over the entire culture cycle—550 g of algal POM and 295 g of detrital POM—of which 284 g

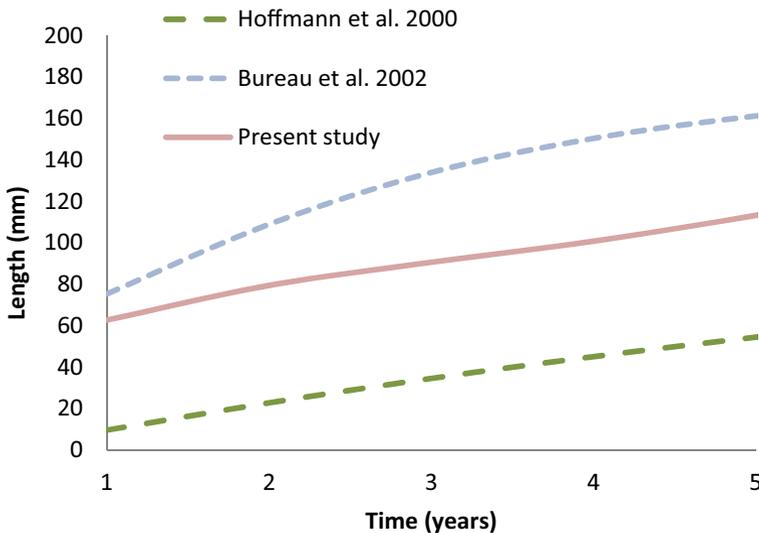


Fig. 4 Comparison between the modeled shell length growth curve of geoduck clams (*Panopea generosa*) of the present study (continuous line) with the maximum (Bureau et al. 2002) and minimum (Hoffmann et al. 2000) growth curves found in the literature (dashed lines)

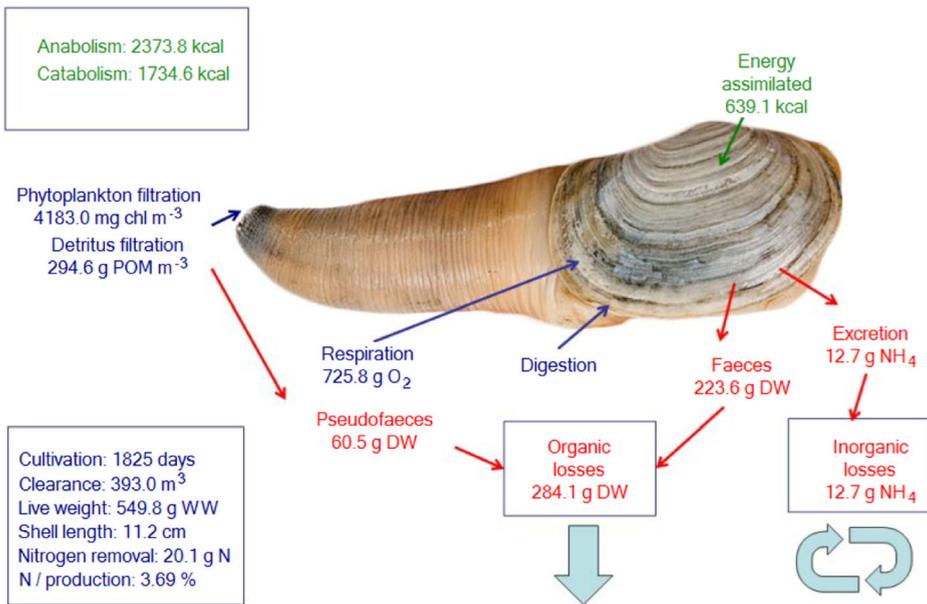


Fig. 5 WinShell mass balance results for an individual geoduck clam (*Panopea generosa*) over a 5-year growth cycle using Eld Inlet environmental data. DW dry weight, N nitrogen, POM particulate organic matter, WW wet weight

(33.6%) is returned to the environment either as pseudofaeces (7.2%) or faeces (26.4%). These organic particles are transferred from the water column to the sediment and may contribute significantly to nitrogen regeneration in the benthos.

Model results showed good agreement with experimental data obtained by Marshall (2012) and Marshall et al. (2014a). The average simulated clearance rate of 9 L h⁻¹ was within the range of values obtained by Marshall (2012) (5.5 to 19 L ind⁻¹ h⁻¹ for the same salinity range) and Marshall et al. (2014b) (7.8 to 14.9 L ind⁻¹ h⁻¹) and close to the 13.2 L ind⁻¹ h⁻¹ average value observed by Marshall (2012) at 11 to 19 °C. The simulated total oxygen consumption (725.8 g) was also within the range of values found by the same author—between 270 and 780 g O₂ per individual for the whole 5-year culture cycle—although close to the upper limit. The scarcity of experimental data on the physiology and growth of geoduck clams hindered the development, calibration, and validation of the individual growth model and highlighted the need for future research in order to improve the knowledge of underlying factors and the quality of bioenergetic models.

Farm-scale production and culture practice

The individual effects discussed above were then scaled to the cultivation area in the FARM model, which provides estimates on production and environmental effects of geoduck farming in the area of the Eld Inlet farm over the whole culture cycle. Table 3 provides a comparison of FARM model outputs with data reported by Chelsea Farms, which shows that the model results are a good match to actual geoduck production. The reported annual harvest is 3.5 t and annualized output from FARM is 2.9 t, considering 560 g total wet weight as the minimum weight for harvest, and a seeding density of 21 ind m⁻². The annualized gross profit

Table 3 Simulated production and environmental effects of geoduck clam (*Panopea generosa*) farming at Chelsea Farms in Eld Inlet (South Puget Sound, Washington, USA) per 5-year cycle

Variable	Model results	Chelsea Farms reported data
Model inputs		
Seed weight (kg total wet weight) per production cycle	111.1	111.4
Model outputs		
<i>Production</i>		
Total physical product (TPP, kg total wet weight)	14,359	17,327
Average physical product (APP, output/input)	129	156
<i>Environmental externalities</i>		
Change in 90th percentile ammonia ($\mu\text{mol L}^{-1}$)	9.00 (in)–9.02 (out)	
Change in 90th percentile chlorophyll (mg chl m^{-3})	16.31 (in)–16.48 (out)	
Change in 10th percentile oxygen concentration (mg L^{-1})	8.43 (in)–8.44 (out)	
ASSETS eutrophication model score	4—No change	
<i>Economics</i>		
Geoduck sales revenue (USD per cycle)	624,629	753,759
Seeding costs (USD per cycle)	27,779	27,850
Farm profit (USD per cycle)	596,850	725,909

determined with FARM is about US\$125,000, which compares reasonably well with the Chelsea Farms' reported profit of US\$145,182.

However, the FARM model takes into account only the seed cost and does not include other production-related costs such as labor and infrastructure, partly because the economic focus of FARM is on marginal analysis. The model estimates a slightly lower return on investment or APP (calculated as the ratio harvestable biomass/seed biomass) than that reported by the farm (Table 3).

The overall outcome of the farm activity is represented in Fig. 6 as an annualized mass balance based on the 1825-day culture cycle. Through the ASSETS (Assessment of Estuarine Trophic Status) model, FARM estimates the nutrients removed from the ecosystem to assess changes in the eutrophication status of the farm and quantify the ecosystem services of geoduck farming. At a culture density of 21 ind m^{-2} , shellfish filtration would annually remove 2543 kg of carbon and 395 kg of nitrogen as phytoplankton and organic detritus. The net removal of nitrogen, after deducting faeces, excretion products, and mortality is 149 kg year^{-1} . Thus, the potential cumulative regulatory ecosystem services provided by geoduck farming correspond to 45 PEQ year^{-1} (1 PEQ = 3.3 kg N year^{-1}) in reducing eutrophication in the area of the Eld Inlet farm. FARM not only makes it possible to simulate the total mass balance of phytoplankton and organic detritus removed, but also the monetary equivalent for nutrient removal, which in this case represents additional potential revenue of approximately US\$1850 year^{-1} (Fig. 6), calculated based on a valuation of US\$12.4 kg^{-1} N (Lindahl et al. 2005). This valuation is at the low end of estimated replacement cost for land-based treatment and could potentially be at least one order of magnitude higher (see review in Ferreira and Bricker 2016). These modeling results support the possibility of integrating shellfish farms such as Eld Inlet farm into a broader, watershed-scale nutrient management plan, in order to create additional revenue opportunities for the farmer and reduce the cost associated with excess nutrient loading at the bay scale.

According to the ASSETS model, at the current geoduck culture density, the eutrophication score of the Eld Inlet farm remained unchanged (Table 3 and Fig. 6). The

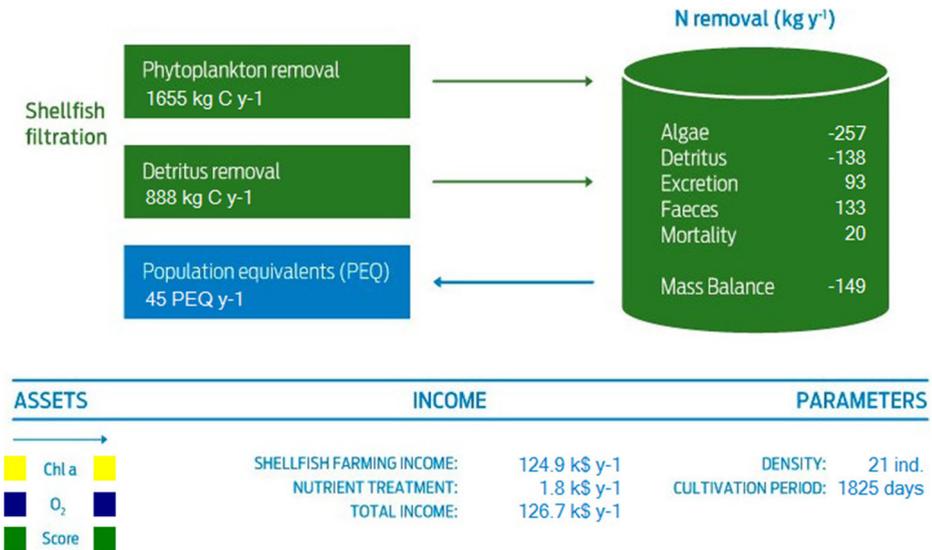


Fig. 6 FARM model annualized mass balance for geoduck clam (*Panopea generosa*) culture at Eld Inlet farm

FARM model results also suggest that there is no significant effect of geoduck culture on the ammonia, dissolved oxygen, and chlorophyll *a* concentrations in the surrounding water (Table 3 and Fig. 6).

The marginal analysis showed that within the range of densities tested (from 10 to 410 ind. m⁻²), the farm still provides higher yields and profits with increasing stocking density, but less return on investment (APP: total production/total seed biomass) due to higher production costs (Fig. 7) (see Ferreira et al. (2007) for full detail of the application and interpretation of marginal analysis in the FARM model). From a food resource perspective, stocking density could still be increased from the 0.11 t currently seeded in the Chelsea Farms area up to 0.7 t of seed—six times the current seeding density—to maximize profit (Fig. 7). This conclusion should be interpreted with caution because greater densities would also affect the ecological carrying capacity and potentially negatively impact other cultured and wild species by competing for the same space and food resources. The model was able to reproduce the intraspecific competition effects due to food and space constraints. A reduction in geoduck growth, in both shell length and weight, was observed when the stocking density was increased above 0.7 t of seed. According to the model results, the use of the optimal stocking density would lead to a seeding density of 130 ind. m⁻², which would potentially lead to an increase in negative impacts associated with geoduck farming (e.g., with respect to the social carrying capacity in terms of visual impact) and could thus affect the economic development of the region.

The FARM model allows testing of different farming strategies in order to determine those that lead to optimization of trade-offs in production, environment, and profitability. The environmental effects of geoduck culture increased accordingly with density, leading to higher biodeposition rates, chlorophyll depletion, and ammonia excretion levels. The higher phytoplankton and detritus removal at greater stocking densities would lead to higher potential revenue due to nutrient credit trading, shifting the balance between regulatory and provisioning services.

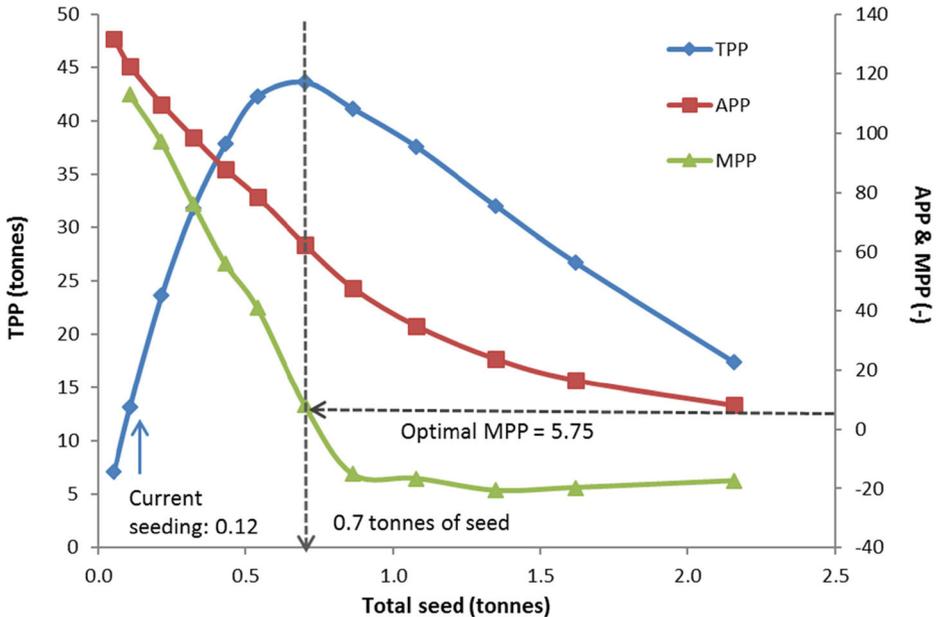


Fig. 7 Marginal analysis curves for geoduck clam (*Panopea generosa*) intertidal culture at the Eld Inlet farm. APP average physical product, MPP marginal physical product, TPP total physical product

Potential ecosystem services provided by geoduck culture in Puget Sound

The overall role of geoduck culture for top-down control of eutrophication symptoms was estimated by upscaling FARM model results to the whole of Puget Sound, considering an annual production of about 730 t (Washington Sea Grant 2015). This scaling exercise assumes that existing farms have the same general culture practice and production per unit area as the Eld Inlet farm and that the results are therefore indicative of conditions typically observed in Puget Sound. However, it does not consider potential interactions among bivalve farms due to food depletion effects. This appears justified because, at present, the density of farms in the sound is relatively low and it is unlikely that contiguous farms will affect each other with respect to availability of phytoplankton or detrital organics. In addition, this study takes into consideration ecosystem services provided only by cultured geoducks without accounting for harvestable wild geoducks—estimated at 88,000 t (193,720,000 pounds)—in Washington (H. Carson, Washington Department of Fish and Wildlife, pers. com.), because our focus was on the cultivation-related impacts. Our results suggest that geoducks would filter 421.5 t of algal C year⁻¹, 226.2 t of detrital C, and would remove 38.0 t N year⁻¹ in the whole Puget Sound. Geoduck culture would provide Puget Sound with an annual ecosystem service for eutrophication control corresponding to 11,462 PEQ or about US\$470,600 in removing primary symptoms of eutrophication.

Geoducks are a niche species, mainly targeting the export market for Asia, but because of their high commercial value are important for the local economy in Puget Sound. Saurel et al. (2014) calculated that the Manila clam (*Venerupis philippinarum*), which has a system-wide production of 4500 t year⁻¹, provides an overall ecosystem service equivalent to almost 88,000 PEQ, i.e., the combined service supplied by both species is equivalent to about 100,000 people and worth in

excess of US\$4,100,000. This is a minimum estimate (Ferreira and Bricker 2016) since it is calculated based on the unit cost for urban areas, whereas the cost for other forms of nutrient removal, such as reconstructed wetlands, can be an order of magnitude higher (Rose et al. 2015).

Conclusions

The models developed and tested herein provide suitable tools for assessing the role of bivalve shellfish in reducing the primary symptoms of eutrophication, which short-circuits the process of organic decomposition and promotes an enhancement of the underwater light climate, improved oxygenation of bottom water, and restoration of submerged aquatic vegetation (Ferreira and Bricker 2016). Such kinds of models can be used to analyze the provisioning and regulatory ecosystem services provided by shellfish farming and assess the potential of including organic-extractive aquaculture into watershed-level, nutrient-credit trading programs in integrated catchment management.

Our results should improve the social acceptance of cultivated shellfish and help enhance their culture in the USA, which is already being leveraged by NOAA. This is important in order to reduce the current dependence of that country on imports of aquatic products (91%) and the corresponding US\$11.2 billion trade deficit (NOAA 2017). Due to the high commercial value and export potential of geoduck clams in Asian markets, particularly in China, geoduck culture should be especially encouraged as a means to promote local employment and trade balance.

Acknowledgements We are very grateful to the Lentz family (in particular Shina Wysocki) for their help with various aspects of the geoduck modeling activity. We also wish to thank Peter Becker and Bill Dewey for their assistance with data and perspectives on farming in South Puget Sound and three anonymous reviewers who commented on a first draft. This work is dedicated to the memory of John Lentz, an aquaculture innovator who enthusiastically supported the PESCA project in promoting sustainability of shellfish culture in the Pacific Northwest of North America.

Funding information Support was from the PESCA project under NOAA grant NA100AR4170057.

References

- Andersen AM (1971) Spawning, growth and spatial distribution of the geoduck clam, *Panopea generosa* Gould, in Hood Canal, Washington. Dissertation, University of Washington, p 133
- Bayne B (2017) Biology of oysters. Developments in aquaculture and fisheries science, volume 41. Elsevier, London
- Bayne B, Worrall CM (1980) Growth and production of mussels *Mytilus edulis* from two populations. Mar Ecol Prog Ser 3:317–328
- Bernard FR (1983) Catalogue of the living Bivalvia of the eastern Pacific Ocean: Bering Strait to Cape Horn. Canadian Special Publication of Fisheries and Aquatic Sciences 61, 102 p
- Brown RA, Thuesen EV (2011) Biodiversity of mobile benthic fauna in geoduck (*Panopea generosa*) aquaculture beds in southern Puget Sound, Washington. J Shellfish Res 30:771–776
- Bureau D, Hajas W, Surry NW, Hand CM, Dovey G, Campbell A (2002) Age, size structure and growth parameters of geoducks (*Panopea abrupta*, Conrad 1849) from 34 locations in British Columbia samples between 1993 and 2000. Can Tech Rep Fish Aquat Sci 2413:84 p
- Bureau D, Hajas W, Hand CM, Dovey G (2003) Age, size structure and growth parameters of geoducks (*Panopea abrupta*, Conrad 1849) from seven locations in British Columbia sampled in 2001 and 2002. Can Tech Rep Fish Aquat Sci:2494, 29 p
- Campbell A, Ming MD (2003) Maturity and growth of the Pacific geoduck clam, *Panopea abrupta*, in Southern British Columbia, Canada. J Shellfish Res 22:85–90

- Chattopadhyay C (2014) Polyphenolics and energy content in phytoplankton: evidence from a freshwater lake. *Proc Zool Soc* 67:18–27
- Ferreira JG, Bricker SB (2016) Goods and services of extensive aquaculture: shellfish culture and nutrient trading. *Aquac Int* 24(3):803–825
- Ferreira JG, Hawkins AJS, Bricker SB (2007) Management of productivity, environmental effects and profitability of shellfish aquaculture—the FARM aquaculture resource management (FARM) model. *Aquaculture* 264:160–174
- Ferreira JG, Hawkins AJS, Bricker SB (2011) The role of shellfish farms in provision of ecosystem goods and services. In: Shumway S (ed) *Shellfish aquaculture and the environment*. Wiley-Blackwell, Chichester, pp 3–32
- Ferreira JG, Saurel C, Ferreira JM (2012) Cultivation of gilthead bream in monoculture and integrated multi-trophic aquaculture. Analysis of production and environmental effects by means of the FARM model. *Aquaculture* 358–359:23–34
- García-Esquível Z, Valenzuela-Espinoza E, Buitimea MI, Searcy-Bernal R, Anguiano-Beltrán C, Ley-Lou F (2013) Effect of lipid emulsion and kelp meal supplementation on the maturation and productive performance of the geoduck clam, *Panopea globosa*. *Aquaculture* 396–399:25–31
- Giles H (2006) Dispersal and remineralisation of biodeposits: ecosystem impacts of mussel aquaculture. Dissertation, University of Waikato, p 170
- Goodwin C, Pease B (1987) The distribution of geoduck (*Panopea abrupta*) size, density, and quality in relation to habitat characteristics such as geographic area, water depth, sediment type, and associated flora and fauna in Puget Sound, Washington. Washington Department of Fisheries, Shellfish Division, Olympia, p 44
- Grant J, Bacher C (1998) Comparative models of mussel bioenergetics and their validation at field culture sites. *J Exp Mar Biol Ecol* 219:21–44
- Gribben PE, Creese RG (2005) Age, growth, and mortality of the New Zealand geoduck clam, *Panopea zelandica* (Bivalvia: Hiatellidae) in two North Island populations. *Bull Mar Sci* 77:119–135
- Hawkins AJS, Duarte P, Fang JG, Pascoe PL, Zhang JH, Zhang XL, Zhu MY (2002) A functional model of responsive suspension-feeding and growth in bivalve shellfish, configured and validated for the scallop *Chlamys farreri* during culture in China. *J Exp Mar Biol Ecol* 281:13–40
- Hoffmann A, Bradbury A, Goodwin CL (2000) Modeling geoduck, *Panopea abrupta* (Conrad, 1849) population dynamics. I Growth. *J Shellfish Res* 19:57–62
- Jolly CM, Clonts HA (1993) *Economics of aquaculture*. Food Products Press, New York
- Kobayashi M, Hofmann EE, Powell EN, Klinck JM, Kusaka K (1997) A population dynamics model for the Japanese oyster, *Crassostrea gigas*. *Aquaculture* 149:285–321
- Lindahl O, Hart R, Hernroth B, Kollberg S et al (2005) Improving marine water quality by mussel farming: a profitable solution for Swedish society. *Ambio* 34:131–138
- Liu W, Pearce CM, Dovey G, (2015) Assessing Potential Benthic Impacts of Harvesting the Pacific Geoduck Clam in Intertidal and Subtidal Sites in British Columbia, Canada. *J Shellfish Res* 34(3):757–775
- Mallet AL, Carver CE, Landry T (2006) Impact of suspended and off-bottom eastern oyster culture on the benthic environment in eastern Canada. *Aquaculture* 255:362–373
- Marshall R (2012) Broodstock conditioning and larval rearing of the geoduck clam (*Panopea generosa* Gould, 1850). Dissertation, University of British Columbia, p 213
- Marshall R, McKinley RS, Pearce CM (2012) Effect of temperature on gonad development of the Pacific geoduck clam (*Panopea generosa* Gould, 1850). *Aquaculture* 338–341:264–273
- Marshall R, Pearce CM, McKinley RS (2014a) Interactive effects of stocking density and algal feed ration on growth, survival, and ingestion rate of larval geoduck clams. *N Am J Aquac* 76(3):265–274
- Marshall R, McKinley RS, Pearce CM (2014b) Effect of ration on gonad development of the Pacific geoduck clam, *Panopea generosa* (Gould, 1850). *Aquac Nutr* 20:349–363
- McDonald PS, Galloway AWE, McPeck KC, VanBlaricom GR (2015) Effects of geoduck (*Panopea generosa*) aquaculture on resident and transient macrofauna communities of Puget Sound, Washington, USA. *J Shellfish Res* 34(1):189–202
- National Oceanic and Atmospheric Administration (2011a) NOAA Aquaculture Policies 2011. http://www.nmfs.noaa.gov/aquaculture/policy/24_aquaculture_policies.html
- National Oceanic and Atmospheric Administration (2011b) National Shellfish Initiative
- National Oceanic and Atmospheric Administration (2016) National Ocean Policy Implementation Plan - Aquaculture http://www.nmfs.noaa.gov/aquaculture/docs/policy/nop_ip_aquaculture.pdf
- National Oceanic and Atmospheric Administration (2017) Aquaculture in the United States. NOAA Fisheries. http://www.nmfs.noaa.gov/aquaculture/aquaculture_in_us.html
- Navarro E, Iglesias JIP, Pérez-Camacho A, Labarta U, Beiras R (1991) The physiological energetics of mussels (*Mytilus galloprovincialis* Lmk) from different cultivation rafts in the Ria de Arosa (Galicia, NW Spain). *Aquaculture* 94:197–212

- Newell RIE (2004) Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. *J Shellfish Res* 23:51–61
- Nizzoli D, Welsh DT, Viaroli P (2011) Seasonal nitrogen and phosphorus dynamics during benthic clam and suspended mussel cultivation. *Mar Pollut Bull* 62:1276–1287
- Orensanz JML, Hand CM, Parma AM, Valero J, Hilborn R (2004) Precaution in the harvest of Methuselah's clams—the difficulty of getting timely feedback from slow-paced dynamics. *Can J Fish Aquat Sci* 61:1355–1372
- Palavesam A, Beena S, Immanuel G (2005) A method for the estimation of detritus energy generation in aquatic habitats. *Turk J Fish Aquat Sci* 5:49–52
- Powers MJ, Peterson CH, Summerson HC, Powers SP (2007) Macroalgal growth on bivalve aquaculture netting enhances nursery habitat for mobile invertebrates and juvenile fishes. *Mar Ecol Prog Ser* 339:109–122
- Ren JS, Ross AH, Hayden BJ (2006) Comparison of assimilation efficiency on diets of nine phytoplankton species of the greenshell mussel *Perna canaliculus*. *J Shellfish Res* 25:887–892
- Rose JM, Bricker SB, Ferreira JG (2015) Comparative analysis of modeled nitrogen removal by shellfish farms. *Mar Pollut Bull* 91(1):185–190
- Saurel C, Ferreira JG, Cheney D, Suhrbier A, Dewey B, Davis J, Jordell J (2014) Ecosystem goods and services from Manila clam culture in Puget Sound: a modelling analysis. *Aquac Environ Interact* 5:255–270
- Sloan NA, Robinson SMC (1984) Age and gonad development in the geoduck clam *Panope abrupta* (Conrad) from southern British Columbia, Canada. *J Shellfish Res* 4:131–137
- Tenore KR (1981) Organic nitrogen and caloric content of detritus. *Estuar Coast Shelf Sci* 12:39–47
- Tiller R, Gentry R, Richards R (2013) Stakeholder driven future scenarios as an element of interdisciplinary management tools; the case of future offshore aquaculture development and the potential effects on fishermen in Santa Barbara, California. *Ocean Coast Manag* 73:127–135
- Tušnik P (1985) Raziskovanje bioloških in eko-fizioloških značilnosti školjk *Mytilus galloprovincialis* Lamarck gojenih v čistem in onesnaženem okolju. Dissertation, University of Ljubljana
- Vadopalas B, Davis JP, Friedman CS (2015) Maturation, spawning, and fecundity of the farmed Pacific geoduck *Panopea generosa* in Puget Sound, Washington. *J Shellfish Res* 34(1):31–37
- Vanblaricom GR, Eccles JL, Olden JD, Mcdonald PS, (2015) Ecological Effects of the Harvest Phase Of Geoduck (Gould, 1850) Aquaculture on Infaunal Communities in Southern Puget Sound, Washington. *J Shellfish Res* 34 (1):171–187
- Washington Sea Grant (2015) Shellfish aquaculture in Washington state. Final report to the Washington State Legislature, p 84
- Widdows J, Hawkins AJS (1989) Partitioning of rate of heat dissipation by *Mytilus edulis* into maintenance, feeding and growth components. *Physiol Zool* 62:764–784
- Zhou Y, Yang H, Zhang T, Qin P, Xu X, Zhang F (2006) Density-dependent effects on seston dynamics and rates of filtering and biodeposition of the suspension-cultured scallop *Chlamys farreri* in a eutrophic bay (northern China): an experimental study in semi-in situ flow-through systems. *J Mar Syst* 59:143–158

Affiliations

Alhambra Martínez Cubillo¹ · João Gomes Ferreira² · Christopher Michael Pearce³ · Robert Marshall⁴ · Dan Cheney⁵ · Bobbi Hudson⁵

✉ Alhambra Martínez Cubillo
alhambra.cubillo@longline.co.uk

¹ Longline Environment Ltd., 88 Wood Street, London EC2V 7RS, UK

² DCEA, Faculdade Ciências e Tecnologia, Universidade Nova de Lisboa, Quinta da Torre, 2829-516 Monte de Caparica, Portugal

³ Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC V9T 6N7, Canada

⁴ Mac's Oysters Ltd., Fanny Bay, BC V0R 1W0, Canada

⁵ Pacific Shellfish Institute, Olympia, WA 98501, USA