Protect Zangle Cove
Post Office Box 1786
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In coalition with:
Coalition to Protect Puget Sound Habitat
APHETI
Washington Sierra Club - Aquaculture
Friends of Anderson Island Shoreline
Friends of Burley Lagoon
Case Inlet Shoreline Association
Citizens of Harstine Island and Shine Beach

January 20, 2015

Tony Kantas, Senior Planner
Thurston County Planning Department
2000 Lakeridge Drive SW
Olympia, WA 98502-6045

Re: **Cumulative Impacts: Comments on Confluence Environmental Company Response to Public Comments**

Applicant: ChangMook Sohn Industrial Geoduck Farm Application
Property: 930 76th Ave NW, Parcel No. 12911440101
Case No. 2014108800

Dear Mr. Kantas,

As citizens, members of Protect Zangle Cove and property owners who live on Zangle Cove in Boston Harbor, Thurston County, we submit the following comments regarding the Confluence Environmental Company ("Confluence") response to public comments, dated November 20, 2015 ("Confluence Report") and submitted for the above application.

This letter specifically addresses the comments made by Confluence regarding the cumulative impacts of the proposed Sohn geoduck farm. Comments on other aspects of the Confluence Report have been and will be set forth in other communications.

Summary:

- A study entitled "Evaluating trophic and non-trophic effects of shellfish aquaculture in a coastal estuarine foodweb" by Bridget E. Ferriss, et al, (Ferriss Study) was published in 2015 under the auspices of Washington Sea Grant, the University of Washington and the National Marine Fisheries Service. This study was specifically related to expansion of geoduck aquaculture in Central Puget Sound. The full report is attached.

- The Confluence Report incorrectly suggests that the issue of cumulative impacts of geoduck farms is irrelevant in the case of the Sohn geoduck farm on Zangle Cove.

- Confluence incorrectly dismisses the conclusions of the recent Ferriss Study that aquaculture gear at a certain level will cause cumulative impacts to the food web.

- Confluence fails to acknowledge that the amount of aquaculture acreage in South Puget Sound has most likely already passed the tipping point based on the Ferriss Study.

- The Confluence Report is a paid advocacy piece which includes industry talking points and should not be considered a scientific document.

- **The recently published Ferriss Study provides a clear basis for a decision to stop permitting all new shellfish aquaculture applications until there is clear scientific evidence that the cumulative impacts of shellfish aquaculture on the tidelands of South Puget Sound is not harmful.**

Details:

The Totten Inlet Experience

For 10 years citizens in Totten Inlet have been saying "the birds are gone" and they blame it on the massive amount of shellfish aquaculture on every elevation level of the beach. In some areas there is virtually no beach left, as we understand the meaning of "beach." 90-95% of the tidelands in Totten Inlet have been converted to industrial aquaculture: geoduck, clam and oyster aquaculture along with extensive mussel raft culture. We don't believe that citizens are saying that there are absolutely no birds left in Totten Inlet, but that **they observe that what used to be there in the way of various bird populations has been dramatically altered.**

This claim by citizens has been routinely dismissed and scorned by the shellfish industry.

The Ferriss Study Projects Cumulative Impacts in Central Puget Sound

Now, in 2015, a University of Washington Study has been published which confirms that both bird and salmon habitat can be casualties of the shellfish aquaculture geoduck industry. This recent study, "*Evaluating trophic and non-trophic effects of shellfish aquaculture in a coastal estuarine foodweb*" by Ferriss, Reum, McDonald, Farrell, and Harvey, October 13, 2015, published in the ICES Journal of Marine Science (Ferriss Study), is alarming in its implications for the cumulative impacts on natural habitat and native species in Puget Sound.

The Ferriss Study uses advanced ecosystem modeling tools to evaluate the likely impacts of expanded intertidal geoduck farming in Central Puget Sound, an area that has far less commercial aquaculture development than South Puget Sound.[1] For the first time an estimate of the impacts includes the use of predator exclusion devices (PVC tubes and nets) and geoduck harvesting methods to evaluate the likely impacts on other species such as birds, salmon, eagles and other species and on the larger food web.

The study projects that doubling the area under geoduck cultivation (120% increase over a projected period of 50 years) is expected to exceed the ecological carrying capacity of Central Puget Sound and incur dramatic impacts on many species.

Some of these alarming impacts include (see the full report):

Decreases in great blue heron:	- 23 %
Decreases in resident eagles:	- 20 % approx.
Decreases in resident birds:	- 17 %
Decreases in wild juvenile salmon:	- 7 %
Decreases in hatchery juvenile salmon:	- 4 %
Increases in surf perch:	+ 25 % approx.
Increases in small crabs:	+ 20 % approx.
Increases in demersal fish:	+ 10 % approx.

This is not simply a matter of arguing the advantages and disadvantages of geoduck tubes, nets and harvesting using stinger pressure jets, though Confluence tries to use this type of argument, claiming for example that:

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[1] The Central Basin of Puget Sound, according to Wikipedia, reaches from the Tacoma Narrows north to the southern shore of Whidbey Island. South Puget Sound is thus everything south of the Narrows.

1) "Aquaculture gear is similar (or superior) to adjacent eelgrass habitat in terms of the diversity and abundance of benthic fauna and fish..."[2]

2) "Aquaculture gear can both provide a new substrate for herring spawn attachments…or provide additional protection from predators such a scoter ducks..."[3]

3) "...when tubes are present, area nets provide cover that not only protects geoducks, but also provides a camouflage layer over the tubes"[4]

Citizens can equally argue that some species are impaired because tubes and nets limit the natural feeding habitat on the tideland, that eagles have become caught in geoduck nets and that claiming toxic PVC tubes are as good as or better than eelgrass is not a rational comparison.

This is not just a battle about winners and losers related to species. It is about the profound magnitude of alteration of an entire South Sound habitat, one that has overall and long-term consequences, as the Ferriss Study points out. Shellfish industry aquaculture in Puget Sound isn't just about one little farm, i.e., the proposed Sohn geoduck farm. It is about changing the face of the Puget Sound intertidal habitat as fast as the industry can change it – **the geoduck gold rush**.

Confluence claims on Page 19, Paragraph 3 of their document that "*the extent of aquaculture is limited by substrate and beach topography in Puget Sound. Therefore, it is unlikely that shellfish aquaculture will ever occur at densities sufficient to present water quality problems from nutrient accumulation*."

This may be true from one point of view if strictly related to problems from nutrient accumulation. But from another point of view, it means that the shellfish aquaculture industry will eventually transform all beaches of a certain type to shellfish aquaculture—permanently altering that complete subset of beach types in the Puget Sound aggregate of all beach types. For example, 90% of Totten Inlet beaches are already altered. It would be the equivalent of planting 43,500 PVC pipes per acre in all the parks in the city of Olympia and saying it is OK because it is not the entire city. Each beach type is a part of the whole system.

Highlights from the Ferriss Study – Cumulative Impacts

In the Ferriss Study similar species are grouped together as a ***functional group***. For example, California Sea Lion and Stellar Sea Lion are included in the functional group "Sea Lions." The Ferriss Study grouped many species into about 80 functional groups. ***Mediation functions*** are a tool to simulate the effects of the changes to the predator-prey relationships that are caused by aspects of geoduck farms (PVC tubes, nets, harvesting, etc.) The biomass of functional groups that were linked to geoduck culture through mediation functions changed considerably, with the biomass densities of some groups increasing and decreasing by over 20% (e.g. surfperch, small crabs, predatory gastropods, and small mouth flatfish; Figure 2) and other functional groups decreasing substantially (e.g. eagles, herons, and so forth). These changes in the biomass of functional groups are directly linked to geoduck culture, propagated through the food web, and contributed to additional changes to biomass in other groups (Figure 2 and Supplementary Table S4).

In total, the biomasses of 9 of the 10 major functional groups with cultured geoduck mediation functions changed substantially and were among the top 20 groups demonstrating the greatest change in biomass. The 9 groups include:

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[2] Confluence Report, Page 18, Paragraph 2
[3] Confluence Report, Page 17, Paragraph 2
[4] Confluence Report, Page 15, Paragraph 3

- Small mouth flatfish
- Piscivorous flatfish
- Demersal fish
- Surfperch
- Small crabs
- Predatory gastropods
- Large infaunal bivalves (group 1)
- Large infaunal bivalves (group 2)
- Small crustaceans

Thus the Ferriss Study predicts strong impacts on the food web of Puget Sound and these impacts may be devastating to many species.

120% over a 50 Year time-period in Central Puget Sound

Please note that Confluence does not mention the fact that the Ferriss Study projects the time of increase to 120% of carrying capacity **over a period of 50 years**. That would presumably be a very slow increase in the number of geoduck farms—slow enough to do more studies and determine even more accurately the cumulative impacts.

We would like to point out that between the date of this calculation of 120% and today, it is likely that the geoduck farms in Central Puget Sound have already increased by 120%, meaning that based on the study, all future geoduck farms in the Central Basin should be precluded as a matter of course, because **the tipping point, based on the study, has already been reached.**

Additionally, because the shellfish industry undoubtedly intends to increase to well over 120% within 5 years (rather than 50 years), that will change the equation. If, as the study says, that at the time of the study the "current cultured geoduck standing stock is approximately 0.1% of the estimated ecological carrying capacity in Central Puget Sound," then over a 50 year period the expansion of geoduck aquaculture should be limited to a total of 1.2 % bringing the total to approximately 1.3% of the ecological carrying capacity. Whatever the calculation of this is as to acreage, it should be divided equally so only an additional 1/50 of that calculation should be allowed per year for new geoduck aquaculture. This is the logic the Ferriss Study is based on.

Central Puget Sound vs. South Puget Sound

The Ferriss Study is specifically related to Central Puget Sound. However, in terms of geoduck aquaculture, South Puget Sound, which includes Thurston County as well as portions of Pierce County and Mason County, is far more developed than either Central or Northern Puget Sound. Industrial geoduck farming techniques started in South Puget Sound prior to 2004-2005 and proliferated rapidly.

In 2012 the harvest of geoduck aquaculture in Central Puget Sound was 23,000 pounds according to the University of Washington (Science Daily, October 22, 2015). **In that same time frame the harvest of geoduck aquaculture in South Puget Sound was approximately 1,000,000 pounds**. That is dramatically more development than Central Puget Sound.

It is NOT appropriate, therefore, to apply the 120% increase to South Puget Sound, because aquaculture in South Puget Sound has likely already exceeded carrying capacity—probably several years ago.

Please consider these important details:

- Though the Ferriss Study points to geoduck predator exclusion devices and harvest techniques in Central Puget Sound, these devices and techniques are in much wider use in South Puget Sound, especially in areas like Totten Inlet, where more than 90 percent of the tideland has been converted to aquaculture use, and also in Eld Inlet, Harstene Island and other areas.[5]

- Because of areas such as Totten Inlet, Eld Inlet and Harstene Island, the composite of the South Puget Sound tidelands of Thurston, Mason and Pierce Counties may have already passed the ecological carrying capacity threshold for impacts on the identified species.

- In discrete areas such as Totten Inlet, there is no doubt that based on this study carrying capacity threshold was reached years ago.

- These facts make it even more imperative that areas in South Puget Sound that are currently still in a pristine state, such as the Zangle Cove area of Mr. Sohn's proposed geoduck farm, should be preserved as a natural estuary.

Confluence Interpretation of the Ferriss Study Related to Cumulative Impacts

The interpretations of the Ferriss Study by Confluence Environmental Company are not supported by the authors of the Ferriss Study and represent an unsubstantiated critique and dismissal of the Ferriss Study findings. The authors of the Ferriss Study noted that their approach was conservative where information was limited or non-existent. Based on the findings in Central Puget Sound, the authors rightly recommend additional scientific research on the cumulative impacts of geoduck farming techniques. That does not diminish the alarming findings of this study.

The shellfish industry, Confluence Environmental Company and the ACERA Biological Evaluation for the proposed Sohn geoduck farm make the frequent claim that geoduck operations have minimal to no effect on habitat and species. Based on the Ferriss Study, this can no longer be accepted. Permits and applications that make this claim must be immediately rejected.

Confluence argues that the Sohn geoduck farm will not have Cumulative Impacts

In general, Confluence talks about the impacts of *only* the proposed Sohn geoduck farm--with the overall justification that one little geoduck farm that is .2 miles away from the next little geoduck farm, is not going to hurt anything. **This is precisely how the proverbial "death by a thousand cuts" happens.** The Ferriss Study looked at the entire Central Puget Sound basin, not just one little geoduck farm. To think about one geoduck farm without the context of the entire system is limited thinking at best.

The issue of cumulative impacts means placing this one small geoduck farm in context with all the rest of the large and small geoduck farms in all of South Puget Sound—from the "filled to capacity" belly of Totten Inlet to the still enticing morsels of pristine tidelands such as Zangle Cove.

- **Page 19, Paragraph 3**: Confluence argues that a 2008 study estimated that Totten Inlet would be at 10% of its carrying capacity if the North Totten mussel farm reached full production. The proposed geoduck operation near Zangle Cove will impact carrying capacity to a much lesser degree than the mussel rafts on Totten Inlet.

[5] See attached map of geoduck farms in South Puget Sound

This is a false argument because it is related to consumption of phytoplankton from the Totten Inlet mussel rafts, not the gear, nets, tubes, oyster bags, clam bags that cover the beaches and that are discussed in the Ferriss Study. Confluence appears be carefully avoiding the topic of gear on the beaches.

- **Page 19, Paragraph 4**. Confluence claims that geoduck aquaculture leads to low to moderate levels of inorganic nutrients but these are dissipated following harvest, tidal action, wave energy, etc.

  Again, this is only thinking in terms of nutrients in the water, it does not include the use of gear—tubes, nets, harvest equipment, harvest itself—the non-trophic elements that are examined in the Ferriss Study. The Zeigler farm on Zangle Cove, for example, now uses some kind of oyster or clam bags at a higher elevation than the geoduck portion of that farm.

- **Page 2, Paragraph 2**. Geoduck farms have a positive cumulative and mitigating effect on water quality.

  The importance of the Ferriss Study is that it goes beyond the impacts on water quality and talks about the impacts of the industrial use itself and industrial gear on the tidelands.

- **Page 20, Paragraph 3**. In this paragraph Confluence basically questions the assumptions used by the authors of the Ferriss Study and claims that the Ferriss Study model is incorrect. Confluence points to an oyster study in Willapa Bay and another study about Dungeness crab and English Sole to support their opinion.

  The comments by Confluence are a diversion and are not based on the actual scientific study of geoduck aquaculture in South Puget Sound. The authors of the Ferriss Study were clear in their indication that additional research is needed. They did not dismiss their own findings because of unanswered questions. It would seem appropriate, before accepting the Confluence opinion on this study, to ask the authors of the Ferriss Study to respond to the Confluence comments.

- **Page 20, Paragraph 3**. Confluence claims that the Ferriss Study didn't mean anything because it was "only intended to be used to identify new research priorities and potential pathways of effect, and was not intended to be used as a way to represent realistic impacts from an increase in gear associated with geoduck aquaculture operation."

  As a reading of the study itself can confirm, this interpretation of the Ferriss Study is not supported by the authors. In fact, in regards to the potential non-trophic impacts to other species in Puget Sound, the authors of the study state:

  "Understanding these relationships can inform management decisions by clarifying trade-offs in ecosystem functions and services in Puget Sound and facilitates estimation of direct and cumulative effects of bivalve aquaculture at a foodweb scale."

  It appears that Confluence is happy to quote the study as definitive when it comes to minimal trophic effects, but is dismissive of the devastating non-trophic effects.

  Please have Confluence get confirmation of their opinion as to the intention of the authors of the Ferriss Study in writing. If the Confluence interpretation of the study is accurate, then their interpretation is an equally good argument for halting the geoduck farm to do additional cumulative impact studies. Having a report such as the Ferriss Study is like having a big sign that says "Cliff Ahead." Do we pay attention to that sign or do we run over the cliff in spite of the sign?

While making use of the Ferriss Study to support its own arguments that phytoplankton are not impacted, Confluence ignores other conclusions of the study related to changes in the habit/food web because of the gear, nets and harvesting. This identifies Confluence as a paid advocate rather than an independent environmental consultant.

Confluence claims that geoduck aquaculture can mitigate for population growth

Page 20, Paragraph 1. In a preposterous statement, Confluence claims that **"shellfish, through their ability to sequester carbon and nitrogen in their shell and tissue, may offer some, albeit slight, mitigation for population growth".**

If this is indeed true, it is surely the best argument we have heard for leaving native geoducks alone to do their job rather than harvesting them in mass from the subtidal and intertidal areas of Puget Sound. Geoducks populations should be completely left alone—*to save the world from population growth*!

On the other hand, if Confluence finds it legitimate to use "mitigation for population" growth as an argument in favor of geoduck aquaculture, then we request that all impacts of geoduck aquaculture as a whole be considered:

1. The cost of producing toxic PVC tubes;
2. The cost in landfill waste of discarded toxic PVC tubes;
3. The environmental cost of escaped PVC tubes, nets, rubber bands;
4. The carbon impact of production of PVC pipes, nets, gear;
5. The carbon impact of transporting thousands of geoducks to Asia;
6. The fact **that geoduck production encourages population growth because geoducks are considered an aphrodisiac in Asia.**

Making arguments such as the one about "mitigating population growth" is a political device, a diversion from the issue and is political grandstanding rather than scientific discourse.

Confluence Message: This little geoduck farm isn't going to hurt anything, so what is everybody so excited about?

The basic argument that Confluence is using in the current paper supporting the proposed Sohn geoduck farm is: this little geoduck farm isn't going to hurt anything, so what is everybody so excited about? But historically, as we have stated above, "one more little geoduck farm" will inevitably lead to Totten Inlet.

We request that Thurston County read the Ferriss Study and take into account the cumulative impacts of aquaculture gear from this farm along with all the current farms in South Puget Sound.

Confluence writes on Page 19: **"impacts from projects in the action area will likely occur in the future."** This sounds as though Confluence already knows where it is going to target the next geoduck farm in Zangle Cove. The County should request that Confluence explain the meaning of this statement.

The most important point, however, is that the Ferris study concludes that cumulative impacts are not just the trophic impacts to phytoplankton, water quality and gear impacts to organisms on the individual farm. **The Ferriss Study points to cumulative impacts to the food web in the entire ecosystem. Thus the impacts reach much further than the closest farms at .2 miles, but include all of South Puget Sound, and in fact the entire Puget Sound ecosystem.**

Cumulative Impacts and Paid Consultants

The Confluence Environmental Company website[6] states that providing services to shellfish aquaculture companies is one of their main project areas:

> ***Regulatory Compliance and Permitting for Shellfish Aquaculture***
> *Confluence Environmental Company staff have provided regulatory compliance and permitting strategies; developed biological assessments, habitat plans, and permitting documents; researched shellfish ecology; and developed study designs for a wide range of shellfish aquaculture projects.*
> *http://www.confenv.com/projectsCaseStudiesShellfish.html*
>
> *Confluence Environmental Company staff have worked with shellfish growers for many years and have provided regulatory compliance and permitting strategies; developed biological assessments, habitat plans, and permitting documents; researched shellfish ecology; and developed study designs for a wide range of shellfish aquaculture projects. By recognizing the stewardship and intrinsic connections between growers and the aquatic environment, clients such as Pacific Coast Shellfish Growers Association, Coast Seafoods, Taylor Shellfish Resources, and Northern Oyster have benefited from our expertise and understanding of resource agencies and their regulatory responsibilities.*

Since the business objective of Confluence is to advocate for their shellfish industry clients, any document submitted by Confluence should be considered a paid advocacy piece and not scientific evidence.

Given the inherent bias on the part of Confluence, it is no surprise that Confluence fully supports the proposed aquaculture operation by Sohn. Confluence is a paid advocate and their document should not be considered as "science." Confluence cherry picks what is included in its advocacy. Some arguments they make, such as "upland property owners are worse," are typical industry talking points, not scientific arguments. **This particular argument is actually a concession by Confluence that aquaculture itself has negative impacts.**

Many of the arguments from Confluence are "as old as the hills" and can be found in past submissions from the shellfish industry. We hope that Thurston County will hold Confluence and other environmental consulting firms to a higher standard and understand that they are politically and monetarily driven, not environmentally driven.

PZC requests to Thurston County related to the proposed Sohn geoduck farm and any other proposed geoduck farm in Thurston County

Based on the results of the Ferriss Study, here in Thurston County immediate action should be taken to:

1. Halt or freeze all geoduck shellfish applications that are in process but not yet approved.
2. Halt all new applications for geoduck shellfish operations.
3. Halt or freeze all application renewals for geoduck shellfish operations.
4. Engage the wider scientific community in a study of South Puget Sound using the same or similar ecological and foodweb simulation models. The authors of the study note that additional information should be included in the study.

[6] http://www.confenv.com/projectsCaseStudiesShellfish.html

5. Adopt the precautionary principle when evaluating all new or renewing shellfish aquaculture operations.

The Ferriss Study provides a clear basis for the above approach. No new shellfish aquaculture activity should be approved until there is clear scientific evidence that it is not harmful. The burden of proof of no harm must be on the commercial shellfish industry.

As shoreline property owners, we are willing to comply with the set-back ordinances and other rules for upland properties that help to protect Puget Sound. It is not thus consistent that the County even consider permits to put over 43,500 plastic PVC tubes on the tidelands, between ***7 and 10 miles of PVC pipe per acre***, depending on the length of the pipe (10-15 inches) and to dredge those tidelands to a depth of three feet harvest. **According to the Ferriss Study, these practices do impact the ecological system of the tidelands and Puget Sound.**

We hope County Officials will take the time to read the attached Ferriss Study and to realize that much of the geoduck aquaculture industry rhetoric has a no relationship to reality—a reality seen accurately years ago by the Totten Inlet citizens group, APHETI.

Our elected officials and government agencies bear ultimate responsibility for the protection of Puget Sound.

Please read the attached copy of the study and respond to our request to halt all current, new, and renewing shellfish aquaculture permit applications.

Sincerely,

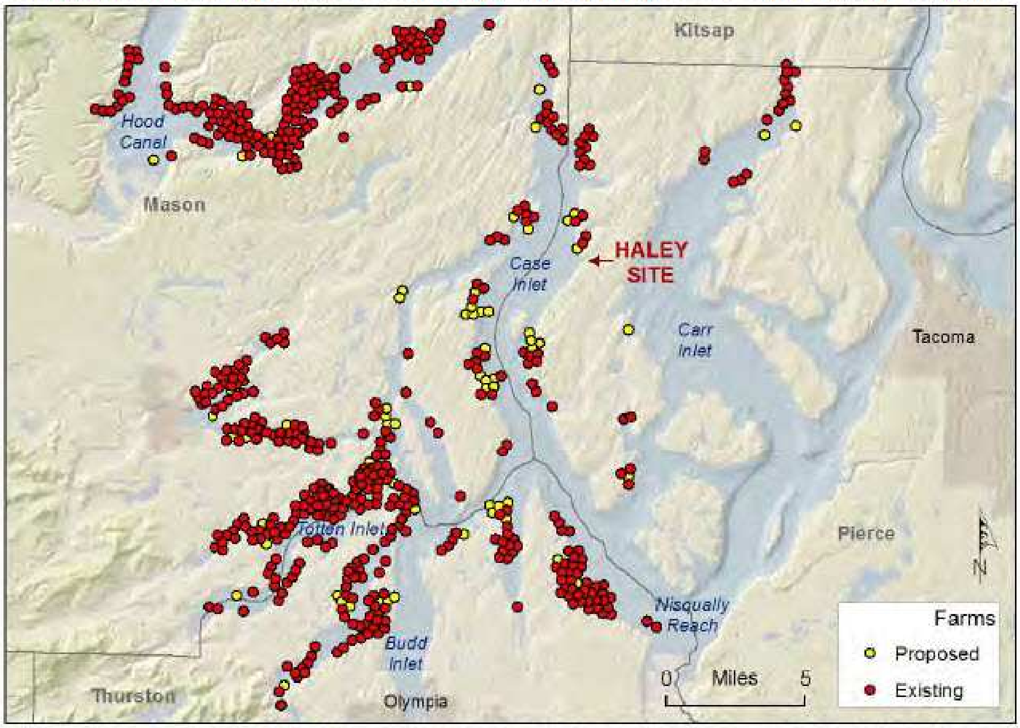
Patrick and Kathryn Townsend
Protect Zangle Cove

Attachment:
"Evaluating trophic and non-trophic effects of shellfish aquaculture in a coastal estuarine foodweb", Ferriss, Reum, McDonald, Farrell, and Harvey, October 13, 2015, ICES Journal of Marine Science.
Map

Cc:
Jessica Jensen, Attorney at Law
Cindy Wilson, Thurston County Senior Planner
Jeremy Davis, Thurston County Senior Planner
Michael Kain, Thurston County Planning Manager
Scott McCormick, Thurston County Associate Planner
Pamela Sanguinetti, Army Corps of Engineers, Seattle Regional Office

Attachment: Coastal Geologic Services Map of existing and proposed shellfish farms in South Puget Sound as of 2014.

Cumulative Impacts: existing and proposed shellfish farms



Known existing and proposed shellfish farm locations in South Puget Sound, totaling 625 in best-available 2012-2014 data.

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Evaluating trophic and non-trophic effects of shellfish aquaculture in a coastal estuarine foodweb

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Ferriss, B. E., Reum, J. C. P., McDonald, P. S., Farrell, D. M., and Harvey, C. J. Evaluating trophic and non-trophic effects of shellfish aquaculture in a coastal estuarine foodweb. – ICES Journal of Marine Science, doi: 10.1093/icesjms/fsv173.

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Expansion of the shellfish aquaculture industry has the potential to affect the structure and dynamics of coastal estuarine foodwebs. To better understand foodweb trade-offs, we incorporated both trophic and non-trophic interactions (e.g. habitat facilitation and predator refuge) into a foodweb model of central Puget Sound to predict the effects of an increase in geoduck (*Panopea generosa*) aquaculture. At a basin scale, the foodweb can support at least 120% increased geoduck aquaculture, above current production levels (landings of 10 546 kg in 2012), with only minor changes in individual species' biomass and/or metrics of ecosystem resilience. The non-trophic effects of increased geoduck aquaculture, related to the influence of anti-predator structure, had a stronger influence on the foodweb than the trophic role of cultured geoducks as filter-feeders and prey to other species. Increased geoduck culture caused substantial increases in biomass densities of surfperch, nearshore demersal fish, and small crabs, and decreases in seabirds, flatfish, and certain invertebrates (e.g. predatory gastropods and small crustaceans). This study identifies species that should be a priority for additional empirical research and monitoring related to bivalve aquaculture interactions, including demersal fish, small crustaceans, and seabirds. It also provides insights into the benefits and challenges of incorporating habitat-related data into a foodweb model. Understanding these relationships can inform management decisions by clarifying trade-offs in ecosystem functions and services in Puget Sound and facilitates estimation of direct and cumulative effects of bivalve aquaculture at a foodweb scale.

Keywords: aquaculture, foodweb, model, non-trophic, shellfish.

Introduction

Bivalve aquaculture is a rapidly growing, global industry that occurs primarily in coastal waters and depends on functioning, productive ecosystems. Interactions between cultured bivalves and the environment can vary with species, grow-out method, harvest and maintenance disturbance regimes, and scale of development (Simenstad and Fresh, 1995; Dumbauld *et al.*, 2009). In regions with both high bivalve densities and water retention times, bivalves may locally deplete phytoplankton (Asmus and Asmus, 1991; Banas *et al.*, 2007), potentially reducing symptoms of eutrophication (Zhou *et al.*, 2006). However, bivalve aquaculture may also alter the composition of benthic communities (Simenstad and Fresh, 1995; Dubois *et al.*, 2007; Dumbauld *et al.*, 2009; Cheney *et al.*, 2012) and influence the abundance and distribution of higher trophic level animals such as seabirds (Connolly and Colwell, 2005; Zydelis *et al.*, 2009; Faulkner, 2013). Understanding these interactions is important to sustainably manage industry expansion and is critical for supporting ecosystem approaches to aquaculture development (NRC, 2010; Cranford *et al.*, 2012).

Foodweb models, such as Ecopath with Ecosim (EwE; Polovina, 1984; Christensen and Walters, 2004), are useful tools for addressing resource management issues in an ecosystem context. To date, applications of EwE to bivalve aquaculture have been restricted to modelling trophic relationships, through their role as filter-feeders and prey to other species (Jiang and Gibbs, 2005; Leloup *et al.*, 2008; Byron *et al.*, 2011b). However, bivalve aquaculture may also have important non-trophic effects. Changes in pelagic–benthic coupling, competition for space, prey concentration, predator refuge, and altered habitat structure (either biogenic structure or gear structure) may change the behavior of species and influence interspecific interactions [see review by Dumbauld *et al.* (2009) and NRC (2010)]. These non-trophic effects of aquaculture are widely documented, but often difficult to incorporate into traditional foodweb models.

Mediation functions are a tool within Ecosim that simulates the influence of a third (mediating) variable on predator–prey interactions, following Wootton's (1994) definition of an interaction modification. Mediation functions can be used to describe non-trophic interactions between species or species and habitats within a foodweb modelling framework (Ainsworth *et al.*, 2008; Ma *et al.*, 2010; Espinosa-Romero *et al.*, 2011; Plummer *et al.*, 2013). For example, mediation functions can be applied to systems in which shellfish farms modify the vulnerability of prey to predators through facilitation (e.g. concentrating prey thereby increasing predation) or protection (e.g. refuge that decreases predation). The mediation effect is the enhancement or dampening caused by the shellfish farm on predator–prey interactions (Christensen *et al.*, 2000). The widespread use of mediation functions is limited by the dearth of knowledge of their functional shape and the strength of the mediating relationships (Harvey, 2014), which typically require regionally specific, empirical data to parameterize. McDonald *et al.*'s (2015) study on the interaction of geoduck aquaculture and the surrounding community provides us with the data needed to overcome these limitations.

Currently, geoduck (*Panopea generosa*) is the most valuable shellfish cultivated in intertidal Washington State. Recent reported landings have approached 589 670 kg with an estimated value of $18 500 000 USD (2010 aquaculture landings estimates, Washington Department of Fish and Wildlife). As suspension-feeders, geoducks have a direct trophic effect on phytoplankton, but non-trophic effects resulting from the cultivation process may also influence community members (McDonald *et al.*, 2012, 2015; Price *et al.*, 2012). Geoduck aquaculture production occurs on a 5–7 year cycle. In the early phase of the cycle, a common practice is to protect newly outplanted juvenile geoduck (i.e. seed) from predators by placing them inside vertically oriented sections of polyvinyl chloride (PVC) tube (10–15 cm diameter) inserted into the tideflat; the tubes are then covered with netting to eliminate predator access (McDonald *et al.*, 2015). Initial stocking density is typically 20–30 clams m^{-2} (VanBlaricom *et al.*, 2015). These anti-predator structures are removed after ~2 years once the clams have reached a size refuge from most predators (McDonald *et al.*, 2015). Market-sized geoducks are eventually harvested individually by hand in the sixth or seventh year in a process of liquefaction, whereby a harvester uses a hose to inject large volumes of low-pressure water into sediments around the clam to loosen and extract it (VanBlaricom *et al.*, 2015). McDonald *et al.* (2015) and VanBlaricom *et al.* (2015) showed, respectively, that anti-predator structure and disturbance resulting from harvest of cultured geoducks can suppress some benthic species while promoting others, and thus culture practices likely have important mediation effects. These empirical data can enable evaluation of geoduck aquaculture expansion on the foodweb and assessment of the relative importance of trophic vs. non-trophic interactions on the community in a single modelling framework.

In the present study, we revised and expanded a previously published EwE model of the central Basin of Puget Sound (Harvey *et al.*, 2012b) to help evaluate the ecological effects of geoduck aquaculture expansion. Central Puget Sound is the largest of four sub-basins that compose Puget Sound, a major fjordal system located in the northwest USA (Figure 1). Currently, central Puget Sound supports significantly less geoduck harvest relative to other major shellfish-producing regions in Washington State, but the potential to develop geoduck culture further exists. In this study, we examined the effects of geoduck aquaculture on the central Puget Sound ecosystem. Specifically, we sought to explore the influence of trophic and non-trophic interactions on biomass predictions in a foodweb model and identify community and ecosystem responses to increased geoduck farming. We first modified an existing, dynamic, mass-balanced foodweb model of central Puget Sound to include cultured shellfish functional groups and added mediation functions that captured the non-trophic effects of geoduck culture on the surrounding foodweb. We subsequently calculated the trophic and non-trophic effects of expanded geoduck aquaculture on community structure under varying scenarios of expansion.

Material and methods

Model development

We modified a recently parameterized EwE model of central Puget Sound (Harvey *et al.*, 2012b) to incorporate ecological relationships between geoduck aquaculture and the larger foodweb. The central Puget Sound model domain drains a total area of 35 500 km^2, encompassing all marine habitat between Tacoma Narrows (47.2681°N, 122.5506°W) in the south and Whidbey Island (47.9013°N, −122.3778°W) in the north (Figure 1). Central Puget Sound includes intertidal habitats dominated by sand, gravel, and occasional eelgrass or algal habitats and mud-bottomed subtidal habitats that exceed depths of 250 m in some areas (Figure 1). In addition, the region includes large bays, many pocket estuaries, and receives freshwater inputs from moderately sized rivers (Cedar River, White River, and Green River; Figure 1).

As a general overview, we first revised the EwE model to include additional taxonomic detail regarding nearshore biota relevant to intertidal bivalve aquaculture. Next, we incorporated mediation functions into the model that corresponded to the non-trophic effects of geoduck culture on other species. The functions were directly informed by field experiments and observations (McDonald *et al.*, 2015) and corresponded to mediation effects that reduced the vulnerability of certain species to predation (i.e. predator refuge) or increased the search rate of predators (i.e. habitat exclusion). Finally, we ran scenarios in Ecosim, simulating increased geoduck aquaculture.

The Ecopath model (Polovina, 1984; Christensen and Pauly, 1992) balances biomass gains and losses for each functional group using the following expression:

$$B_i \cdot \left(\frac{P}{B}\right)_i \cdot EE_i = BA_i + Y_i + \sum_{j=1}^{n} B_j \cdot \left(\frac{Q}{B}\right)_j \cdot DC_{ij} \qquad (1)$$

where the biomass (B), production to biomass ratio (P/B), and ecotrophic efficiency (EE) (the fraction of production used in the system) of prey group i are balanced with the biomass accumulation (BA) and mortalities due to fisheries (Y), and predation by all

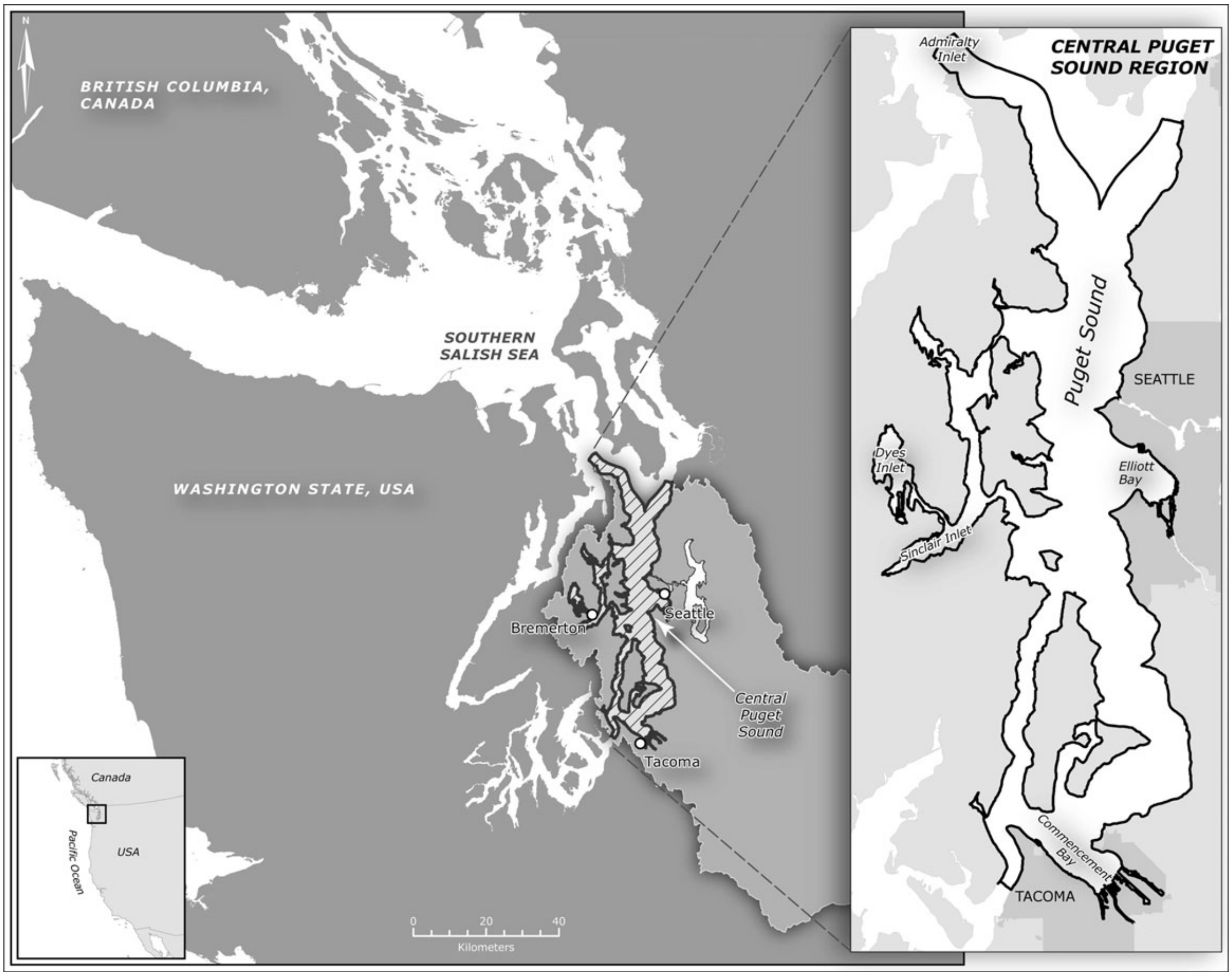

Figure 1. Map of the central Puget Sound, the spatial domain for the EwE model, and the rest of the southern Salish Sea, as well as catchment areas (lightly shaded) that feed directly into central Puget Sound. Inset shows Puget Sound in more detail (Harvey *et al.*, 2012b).

groups *j*. Predation mortality is calculated using the biomass of all predator groups *j*, the consumption to biomass ratio (Q/B) of all predator groups, and the fraction of group *i* in the diet of each group *j* (*DC*). Ecopath uses matrix inversion to calculate one parameter (often *B* or *EE*) for each group based on inputs of the other parameters such as diet, production, consumption, and mortality rates.

Ecosim adds a temporal dynamic to the foodweb model, allowing the biomass of functional groups to change due to trophic dynamics, harvest, other mortality, immigration, and emigration. A set of differential equations are solved in Ecosim, based on the form:

$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (M_i + F_i + e_i)B_i \qquad (2)$$

where $\mathrm{d}B_i{\cdot}\mathrm{d}t^{-1}$ represents the growth rate of group *i*. Biomass increases with net growth efficiency (g_i), total consumption of group *i* (Q_{ji}), and immigration (I_i). Biomass decreases with predation mortality (Q_{ij}) by all predators on group *i*, non-predation mortality (M_i), fishing mortality (F_i), and emigration (e_i).

We revised the central Puget Sound model to include additional detail in nearshore functional groups and cultured geoduck groups (Table 1 and Supplementary Tables S1 and S2). Specifically, we added migratory shorebirds (e.g. dunlins *Calidris alpine*), great blue herons (*Ardea herodias*), small brachyuran crabs, and red rock crab (*Cancer productus*). We also divided the existing infaunal bivalve group into two groups: large- and small-bodied bivalves. Large-bodied bivalves consisted principally of species of interest to recreational and commercial harvesters (e.g. butter clam *Saxidomus gigantean*, horse clam *Tresus capax*, and heart cockle *Clinocardium nuttallii*). Small-bodied bivalves included those not targeted by commercial or recreational harvest (e.g. purple Transennella *Transennella tantilla* and amethyst gem clam *Gemma gemma*).

We added cultured geoducks as a multistanza group, to separate the stages in which anti-predator structure is present (years 1–2), anti-predator structure is absent (years 3–5), and harvest occurs (years 6–7). We calculated the central Puget Sound standing stock biomass based on the 2012 aquaculture landings estimate of 10 546 kg (Washington Department of Fish and Wildlife) and an average geoduck weight of 0.7 kg at harvest. We assumed an estimated natural mortality rate of 50% from outplanting to harvest, with half the mortality occurring in the first 2 years (B. Phipps and J. Gibbons, pers. comm.). We used the von Bertalanffy growth equation to calculate individual growth (maximum length = 158 mm,

Table 1. Functional groups in the EwE model with major representatives.

Functional group	Common name	Scientific classification
Harbour seals	Harbour seal	*Phoca vitulina*
Sea lions	California sea lion	*Zalophus californianus*
	Steller sea lion	*Eumetopias jubatus*
Gulls	Various gulls	*Larus* spp.
Resident diving birds	Various cormorants	*Phalacrocorax* spp.
	Pigeon guillemot	*Cepphus columba*
Migratory diving birds	Western grebe	*Aechmophorus occidentalis*
	Various loons	*Gavia* spp.
	Common murre	*Uria aalga*
Nearshore diving birds	Various scoters	*Melanitta* spp.
	Various goldeneyes	*Bucephala* spp.
Herbivorous birds	Dabbling ducks	*Anas* spp.
	Various geese	*Branta* spp.
Migratory shorebirds	Dunlins	*Calidris alpina*
Great blue herons	Great blue herons	*Ardea herodias*
Raptors	Bald eagle	*Haliaeetus leucocephalus*
Wild salmon	Chum salmon	*Oncorhynchus keta*
	Chinook salmon	*O. tshawytscha*
	Coho salmon	*O. kisutch*
Hatchery salmon	Chum salmon	*O. keta*
	Chinook salmon	*O. tshawytscha*
	Coho salmon	*O. kisutch*
Pink salmon	Pink salmon	*O. gorbuscha*
Pacific herring	Pacific herring	*Clupea pallasii*
Forage fish	Surf smelt	*Hypomesus pretiosus*
	Pacific sand lance	*Ammodytes hexapterus*
Surfperches	Shiner perch	*Cymatogaster aggregata*
	Striped seaperch	*Embiotoca lateralis*
Spiny dogfish	Spiny dogfish	*Squalus acanthias*
Skates	Longnose skate	*Raja rhina*
	Big skate	*R. binoculata*
Ratfish	Whitespotted ratfish	*Hydrolagus colliei*
Pacific hake	Pacific hake	*Merluccius productus*
Pacific cod	Pacific cod	*Gadus macrocephalus*
Walleye pollock	Walleye pollock	*Theragra chalcogramma*
Lingcod	Lingcod	*Ophiodon elongatus*
Rockfish	Copper rockfish	*Sebastes caurinus*
	Quillback rockfish	*S. maliger*
Piscivorous flatfish	Pacific sanddab	*Citharichthys sordidus*
Small-mouthed flatfish	English sole	*Parophrys vetulus*
	Rock sole	*Lepidopsetta bilineata*
Demersal fish	Various poachers	Family Agonidae
	Various eelpouts	*Lycodes* spp.
	Various small sculpins	Family Cottidae
Squid	Opalescent (market) squid	*Loligo opalescens*
Octopus	Red octopus	*Octopus rubescens*
	Giant Pacific octopus	*Enteroctopus dofleini*
Shrimp	Pandalid shrimp	Family Pandalidae
	Sand shrimp	*Crangon* spp.
Cancer crabs	Dungeness crab	*Cancer magister*
Red rock crab	Red rock crab	*Cancer productus*
Sea stars	Sunflower star	*Pycnopodia helianthoides*
	Pink sea star	*Pisaster brevispinis*
Sea urchins	Green sea urchin	*Strongylocentrotus droebachiensis*
	Red sea urchin	*S. franciscanus*
Other grazers	Various snails	Class Gastropoda
	Various chitons	Class Polyplacophora
Small crustaceans	Various amphipods	Suborders Gammaridea, Corophiidea
	Various mysids	Family Mysidae

Continued

Table 1. *Continued*

Functional group	Common name	Scientific classification
Small crabs	Various crabs	Infraorders Brachyura, Anomura
Large sea cucumbers	California sea cucumber	*Parastichopus californicus*
Predatory gastropods	Moon snail	*Euspira lewisii*
	Hairy triton	*Fusitriton oregonensis*
Mussels	Blue mussel	*Mytilus edulis*
Barnacles	Various barnacles	Suborder Balanomorpha
Geoducks	Geoduck	*Panopea abrupta*
Cultured geoduck	Geoduck	*Panopea generosa*
Large infaunal bivalves	Butter clam	*Saxidomus gigantea*
	Horse clam	*Tresus capax*
	Native littleneck clam	*Leukoma staminea*
	Manila clam	*Venerupis philippinarum*
Small infaunal bivalves	Purple Transennella	*Transennella tantilla*
	Amethyst gemclam	*Gemma gemma*
	Charlotte macoma	*Macoma carlottensis*
	Baltic macoma	*Macoma balthica*
Soft infauna	Polychaetes	Class Polychaeta
Deposit feeders	Brittlestars	*Amphiodia urtica*
	Various sea cucumbers	Class Holothuroidea
Suspension-feeders	Various sponges	Phylum Porifera
	Various bryozoans	Phylum Bryozoa
	Sea pen	*Ptilosarcus gurneyi*
Tunicates	Various sea squirts	Class Ascidiacea
Bacteria	Various bacteria	
Microzooplankton	Various microzooplankton	
Copepods	Various copepods	Order Calanoida
Euphausiids	Pacific krill	*Euphausia pacifica*
Small gelatinous zooplankton	Various small jellyfish, ctenophores, and other soft plankton	
Jellyfish	Lion's mane jelly	*Cyanea capillata*
	Moon jelly	*Aurelia labiata*
	Fried egg jelly	*Phacellophora camtschatica*
Macrozooplankton	Various planktonic shrimp, amphipods, and larval crustaceans	
Phytoplankton	Various diatoms, dinoflagellates and phytoflagellates	
Benthic microalgae	Various benthic diatoms	
Benthic macroalgae	Various understory algal species	
Overstory kelp	Bull kelp	*Nereocystis luetkeanus*
Eelgrass	Native eelgrass	*Zostera marina*
Detritus	Not available	
Plant/algal material	Not available	
Salmon carcasses	Not available	*Oncorhynchus* spp.

length at maturity = 75 mm, $k = 0.19$; Bradbury and Tagart, 2000; Calderon-Aguilera *et al.*, 2010), and logistic growth to estimate the number of geoducks over time. We assumed von Bertalanffy growth to keep consistent with the Ecopath biomass calculations for multistanza groups. To determine density ($t\ km^{-2}$), we divided these biomass estimates by the product of total area in central Puget Sound (757.08 km^2; Harvey *et al.*, 2012b) and the proportion of that area in the 0- to 10-m depth range (0.137 km^2; Harvey *et al.*, 2012b). The resulting densities are 5.288 t km^{-2} (years 1–2), 9.689 t km^{-2} (years 3–5), and 5.025 t km^{-2} (years 6–7). The density would be largely underestimated in planted areas and overestimated in unplanted areas. This is consistent with how other Ecopath population densities are estimated.

Mediation

Mediation functions are a tool within Ecosim that can simulate the influence of a functional group or species on the strength of predator–prey interactions between a different pair of species. The consumption rate (Q) of prey (i) by predator (j) is defined in Ecosim as

$$Q = \left(\frac{a_{ij}}{A_{ij}}\right) \cdot \frac{v_{ij} \cdot B_i}{(2V_{ij} + (a_{ij}/A_{ij}) \cdot P_j)} \cdot P_j \qquad (3)$$

where a_{ij} is the rate of effective search for i by j, A_{ij} is the search area in which j forages for i, v_{ij} is the flow rate of biomass (B_i) between pools that are vulnerable or invulnerable to predation, and P_j is the abundance of j in A_{ij}. A mediation function influences a_{ij}, A_{ij}, and (or) v_{ij} according to a user-defined function. An increased v_{ij} makes i subject to greater top-down control and increasing a_{ij} makes j a more efficient consumer of i. Input mediation multipliers range from 0 to 1, and are rescaled by Ecosim to equal one when the biomass of the mediating group is at its initial baseline density.

We included two sets of mediation functions: non-aquaculture-related interactions previously published for the central Puget Sound model (Harvey *et al.*, 2012a; Plummer *et al.*, 2013; Harvey, 2014), and those based on an empirical study of the effects of geoduck culture on macrobenthic communities in South Puget Sound (summarized in Table 2; McDonald *et al.*, 2015). Following Plummer *et al.* (2013), we allowed increasing eelgrass biomass to positively mediate v_{ij} values for the prey of juvenile salmon (i.e. greater top-down control as eelgrass aggregates prey), negatively mediate v_{ij} values for juvenile salmon and young of the year crab (i.e. more bottom-up control as eelgrass increases and provides refuge from nearshore predators), and positively mediate the a_{ij} value for juvenile Pacific herring *Clupea pallasii* (greater juvenile herring productivity as eelgrass increases and provides spawning substrate). Harvey *et al.* (2012a) described a behavioral mediation effect where resident and overwintering bald eagles *Haliaeetus leucocephalus* (the mediating groups) harass nearshore diving and herbivorous seabirds, which causes them to expend more energy to avoid eagle predation while foraging. That is, the variables A_{ij} (of the nearshore diving and herbivorous seabirds) and v_{ij} (of their prey), which relate foraging ability, were modelled as a decreasing function of increasing eagle biomass.

The geoduck aquaculture mediation functions are primarily based on observed numerical responses of benthic invertebrates to anti-predator structure (partially buried PVC tubes with net covers) placed on plots with outplanted geoducks over their first 2 years (Table 2). Functional groups thought to gain refuge from the anti-predator structure, and that exhibited higher biomass densities inside geoduck plots with the anti-predator structure, had mediation functions wherein vulnerability to predation (v_{ij}) decreased as a function of increasing geoduck culture (Table 2). If a prey and its predator species both had higher biomass densities inside geoduck anti-predator structure, we added two separate positive and negative mediation functions on the predation vulnerability of the prey species, as we could not determine how the predator–prey dynamics would play out (e.g. demersal fish prey upon surfperch and both groups had higher biomasses inside geoduck farms; Table 2). For groups that showed lower biomass densities inside geoduck plots and that were thought to be excluded (e.g. flatfish and predatory gastropods, Table 2), their search rates (a_{ij}) were set to decrease as a function of increasing cultured geoduck biomass (Table 2). That is, they became less efficient at finding prey. These geoduck mediation effects were only applied to predator–prey functional groups found in intertidal habitats where geoduck farms are likely to be sited.

McDonald *et al.* (2015) found an anti-predatory structure on geoduck plots to have an exclusionary effect on flatfish and predatory gastropods (moon snail *Lunatia lewisii*), and an attraction effect on demersal fish (e.g. gunnels and shiner perch), small crabs, sea stars, and red rock crabs (Table 2). The small crustaceans and large infaunal bivalve groups were unique in that they had relationships to multiple geoduck stanzas (i.e. the youngest geoduck stanza associated with the anti-predator structure and the oldest stanza subject to harvest). Small crustacean biomass densities (based on *Corophium* amphipods) decreased in geoduck plots with the anti-predator structure, and were assumed to be excluded from the plots (their search rate a_{ij} decreased; Table 2). During the geoduck harvest stage, small crustacean biomass densities increased, and predator refuge was assumed (their vulnerability v_{ij} decreased; Table 2). Large infaunal bivalve biomass (based on the heart cockle) increased in geoduck anti-predator structure (predator refuge; their vulnerability v_{ij} decreased) and decreased during the final, harvest stage of cultured geoducks (habitat exclusion; their search rate a_{ij} decreased; Table 2).

In the absence of empirical data on the shape and strength of these functions, we set the shape of all mediation functions to a hyperbolic function, as this is the most conservative approach (Harvey, 2014), defined as

$$\frac{M_{\min} + (M_{\max} + M_{\min})}{1 + k \cdot B} \qquad (4)$$

where the endpoints are defined by $M_{\max}$ (Ecosim: Y_{zero}) and $M_{\min}$ (Ecosim: Y_{end}), and the curve has a gradient of k (Ecosim: Y_{base}). The values for each parameter were set to 2, 0, and 1, respectively, for all functional groups except small crustaceans. The small crustacean group is composed of mysid shrimps, cumaceans, benthic amphipods (suborders Gammaridea and Corophiide), and benthic isopods. Because benthic amphipods are directly targeted by a cultured geoduck mediation effect (Table 2), but make up only one-third of the small crustacean group as defined by Harvey *et al.* (2012a), we made the functional curve for this mediation effect more conservative while keeping the same hyperbolic trend by setting k to 1.5.

Analysis

Our analysis consisted of two phases. First, we estimated the ecological carrying capacity for cultured geoducks in central Puget Sound and assessed the presence of ecological thresholds related to increasing geoduck aquaculture. Second, we identified trophic and non-trophic effects of geoduck culture on individual functional groups.

Ecological carrying capacity is the biomass of cultured geoducks that can be supported by the existing levels of phytoplankton production [as defined by Harvey *et al.* (2012a)], before the foodweb

Table 2. Mediation effects specific to geoduck culture in Puget Sound (McDonald *et al.*, 2015) and added to the central Puget Sound EwE model.

Species/group (McDonald *et al.*, 2015)	EwE group	Mediation parameter
Starry flounder (*Platichthys stellatus*)	Small mouth flatfish (−)	$-a_{\text{surfperch, small mouth flatfish}}^{(1)}$
Sand sole (*Psettichthys melanostictus*)		$-a_{\text{shrimp, small mouth flatfish}}^{(1)}$
		$-a_{\text{YOY crab, small mouth flatfish}}^{(1)}$
		$-a_{\text{other grazers, small mouth flatfish}}^{(1)}$
		$-a_{\text{small crabs, small mouth flatfish}}^{(1)}$
		$-a_{\text{small mouth flatfish, barnacles}}^{(1)}$
		$-a_{\text{soft infauna, small mouth flatfish}}^{(1)}$
		$-a_{\text{deposit feeders, small mouth flatfish}}^{(1)}$
Speckled sanddab (*Citharichthys stigmaeus*)	Piscivorous flatfish (−)	$-a_{\text{surfperch, piscivorous flatfish}}^{(1)}$
		$-a_{\text{demersal fish, piscivorous flatfish}}^{(1)}$
		$-a_{\text{shrimp, piscivorous flatfish}}^{(1)}$
		$-a_{\text{other grazers, piscivorous flatfish}}^{(1)}$
		$-a_{\text{small crabs, piscivorous flatfish}}^{(1)}$
		$-a_{\text{barnacles, piscivorous flatfish}}^{(1)}$
		$+a_{\text{soft infauna, piscivorous flatfish}}^{(1)}$
Saddleback gunnel (*Pholis ornate*)	Demersal fish (+)	$-v_{\text{demersal fish, sea lions}}^{(1)}$
Pinpoint gunnel (*Apodichthys flavidus*)		$-v_{\text{demersal fish, gulls}}^{(1)}$
Crescent gunnel (*Pholis laeta*)		$-v_{\text{demersal fish, resident birds}}^{(1)}$
Bay pipefish (*Syngnathus leptorhynchus*)		$-v_{\text{demersal fish, migratory birds}}^{(1)}$
Snake prickelback (*Lumpenus sagittal*)		$-v_{\text{demersal fish, great blue herons}}^{(1)}$
Tubesnout (*Aulorhynchus flavidus*)		$-v_{\text{demersal fish, migratory eagles}}^{(1)}$
		$-v_{\text{demersal fish, resident eagles}}^{(1)}$
		$-v_{\text{demersal fish, juvenile wild salmon}}^{(1)}$
		$-v_{\text{demersal fish, juvenile hatchery salmon}}^{(1)}$
		$-v_{\text{demersal fish, piscivorous flatfish}}^{(1)}$
Shiner surfperch (*Cymatogaster aggregate*)	Surfperch (+)	$-v_{\text{surfperch, resident birds}}^{(1)}$
		$-v_{\text{surfperch, migratory birds}}^{(1)}$
		$-v_{\text{surfperch, great blue herons}}^{(1)}$
		$-v_{\text{surfperch, migratory eagles}}^{(1)}$
		$-v_{\text{surfperch, resident eagles}}^{(1)}$
		$-v_{\text{surfperch, juvenile wild salmon}}^{(1)}$
		$-v_{\text{surfperch, juvenile hatchery salmon}}^{(1)}$
		$-v_{\text{surfperch, piscivorous flatfish}}^{(1)}$
		$-v_{\text{surfperch, small mouth flatfish}}^{(1)}$
		$-v_{\text{surfperch, demersal fish}}^{(1)}$
		$+v_{\text{surfperch, demersal fish}}^{(1)}$
		$-v_{\text{surfperch, YOY crab}}^{(1)}$
Red rock crabs (*Cancer productus*)	Red rock crabs (+)	$-v_{\text{red rock crabs, gulls}}^{(1)}$
		$-v_{\text{red rock crabs, resident birds}}^{(1)}$
		$-v_{\text{red rock crabs, demersal fish}}^{(1)}$
		$+v_{\text{red rock crabs, demersal fish}}^{(1)}$
		$-v_{\text{red rock crabs, octopus}}^{(1)}$
		$-v_{\text{red rock crabs, sea stars}}^{(1)}$
		$+v_{\text{red rock crabs, sea stars}}^{(1)}$
Small crabs (Infraorder Brachyuran)	Small crabs (+)	$-v_{\text{small crabs, forage fish}}^{(1)}$
		$-v_{\text{small crabs, surfperch}}^{(1)}$
		$+v_{\text{small crabs, surfperch}}^{(1)}$
		$-v_{\text{small crabs, demersal fish}}^{(1)}$
		$+v_{\text{small crabs, demersal fish}}^{(1)}$
		$-v_{\text{small crabs, sea stars}}^{(1)}$
		$+v_{\text{small crabs, sea stars}}^{(1)}$
Pacific moon snails (*Euspira lewisii*)	Predatory gastropods (−)	$-a_{\text{urchins, predatory gastropods}}^{(1)}$
		$-a_{\text{other grazers, predatory gastropods}}^{(1)}$
		$-a_{\text{mussels, predatory gastropods}}^{(1)}$
		$-a_{\text{barnacles, predatory gastropods}}^{(1)}$
		$-a_{\text{large infaunal bivalves, predatory gastropods}}^{(1)}$
		$-v_{\text{small infaunal bivalves, predatory gastropods}}^{(3)}$
		$+v_{\text{small infaunal bivalves, predatory gastropods}}^{(3)}$
		$-a_{\text{suspension-feeders, predatory gastropods}}^{(1)}$
		$-a_{\text{tunicates, predatory gastropods}}^{(1)}$

Continued

Table 2. *Continued*

Species/group (McDonald *et al.*, 2015)	**EwE group**	**Mediation parameter**
Heart cockles (*Clinocardium nuttallii*)	Large infaunal bivalves ($+^{(1)}/-^{(3)}$)	$-v_{\text{large infaunal bivalves, gulls}}^{(1)}$
		$+v_{\text{large infaunal bivalves, gulls}}^{(3)}$
		$-v_{\text{large infaunal bivalves, nearshore birds}}^{(1)}$
		$+v_{\text{large infaunal bivalves, nearshore birds}}^{(3)}$
		$-v_{\text{large infaunal bivalves, migratory shorebirds}}^{(1)}$
		$+v_{\text{large infaunal bivalves, migratory shorebirds}}^{(3)}$
		$-v_{\text{large infaunal bivalves, surfperch}}^{(1)}$
		$+v_{\text{large infaunal bivalves, surfperch}}^{(3)}$
		$-v_{\text{large infaunal bivalves, piscivorous flatfish}}^{(1)}$
		$+v_{\text{large infaunal bivalves, piscivorous flatfish}}^{(3)}$
		$-v_{\text{large infaunal bivalves, small mouth flatfish}}^{(1)}$
		$+v_{\text{large infaunal bivalves, small mouth flatfish}}^{(3)}$
		$-v_{\text{large infaunal bivalves, demersal fish}}^{(1)}$
		$+v_{\text{large infaunal bivalves, demersal fish}}^{(3)}$
		$-v_{\text{large infaunal bivalves, octopus}}^{(1)}$
		$+v_{\text{large infaunal bivalves, octopus}}^{(3)}$
		$-v_{\text{large infaunal bivalves, YOY crab}}^{(1)}$
		$+v_{\text{large infaunal bivalves, YOY crab}}^{(3)}$
Heart cockles (*Clinocardium nuttallii*)	Large infaunal bivalves ($+^{(1)}/-^{(3)}$)	$-v_{\text{large infaunal bivalves, red rock crab}}^{(1)}$
		$+v_{\text{large infaunal bivalves, red rock crab}}^{(3)}$
		$-v_{\text{large infaunal bivalves, sea stars}}^{(1)}$
		$+v_{\text{large infaunal bivalves, sea stars}}^{(3)}$
		$-v_{\text{large infaunal bivalves, small crabs}}^{(1)}$
		$-v_{\text{large infaunal bivalves, small crabs}}^{(3)}$
		$+v_{\text{large infaunal bivalves, small crabs}}^{(3)}$
		$-v_{\text{large infaunal bivalves, predatory gastropods}}^{(1)}$
		$+v_{\text{large infaunal bivalves, predatory gastropods}}^{(3)}$
Corophium amphipods	Small crustaceans ($-^{(1)}/+^{(3)}$)	$-a_{\text{bacteria, small crustaceans}}^{(1)}$
		$+v_{\text{bacteria, small crustaceans}}^{(3)}$
		$+a_{\text{phytoplankton, small crustaceans}}^{(1)}$
		$+v_{\text{phytoplankton, small crustaceans}}^{(3)}$
		$+a_{\text{benthic microalgae, small crustaceans}}^{(1)}$
		$+v_{\text{benthic microalgae, small crustaceans}}^{(3)}$
		$+a_{\text{benthic macroalgae, small crustaceans}}^{(1)}$
		$+v_{\text{benthic macroalgae, small crustaceans}}^{(3)}$
		$+a_{\text{eelgrass, small crustaceans}}^{(1)}$
		$+v_{\text{eelgrass, small crustaceans}}^{(3)}$
		$+a_{\text{algal/plant matter, small crustaceans}}^{(1)}$
		$+v_{\text{algal/plant matter, small crustaceans}}^{(3)}$
		$+a_{\text{detritus, small crustaceans}}^{(1)}$
		$+v_{\text{detritus, small crustaceans}}^{(3)}$

Sign (+ or −) in the EwE Group column indicates the effect of geoduck culture on the functional group, as observed by McDonald *et al.* (2015). The superscript numbers 1 and 3 associated with the mediation parameter indicate whether the mediation function is based on the effect of anti-predation structure in the first stanza of culture (years 1 and 2) or due to harvest disturbance in the third stanza (years 6 or 7). Mediation parameters correspond to an increase (+) or decrease (−) in the vulnerability (v_{ij}) of the prey (i) or search rate (a_{ij}) on the predator (j).

becomes unbalanced. The foodweb was deemed "unbalanced" when the ecotrophic efficiency of phytoplankton exceeded 1 [as calculated by the mass–balance algorithm described in Equation (1)], and occurs when phytoplankton grazing mortality exceeds total productivity (Jiang and Gibbs, 2005; Byron *et al.*, 2011a). We calculated ecological carrying capacity by incrementally increasing the cultured geoduck biomass and associated landings until reaching the ecological carrying capacity threshold. We increased the cultured geoduck biomass and landings proportional to the base model values.

We calculated changes in ecosystem attributes by using four established indices: the Ecosystem Reorganization Index, the Shannon Diversity Index, Mean Trophic Level (MTL), and Mixed Trophic Impact (Libralato *et al.*, 2006; Samhouri *et al.*, 2010). These attributes describe the capacity of an ecosystem to absorb perturbations while retaining essential structure and function and quantify the ecosystem impact of individual functional groups. The Ecosystem Reorganization Index approximates ecosystem resilience (Folke *et al.*, 2004) by measuring the extent to which perturbations cause changes in the relative biomass of individual functional groups ($B_{t,i}$; Samhouri *et al.*, 2009):

$$R = -\left[\sum_i \left|\frac{B_{t_2,i} - B_{t_1,i}}{\sum_i B_{t_1,i}}\right| - \left|\frac{\sum_i B_{t_2,i} - \sum_i B_{t_1,i}}{\sum_i B_{t_1,i}}\right|\right] \cdot 100 \qquad (5)$$

A value of R farther from 0 indicates lower resilience, implying that the aggregate biomass and the individual functional groups respond differently in magnitude and direction to a pressure. This is a relative index, with 0 as the lower bound (unstressed) and an unlimited upper bound (stressed) dependent on changes

Table 3. Ecosystem attributes measured in response to increased geoduck biomass in the central Puget Sound foodweb.

	Per cent increase in geoduck biomass (t km^{-2})							
Attributes	**20**	**70**	**80**	**90**	**100**	**110**	**120**	**Unstressed state**
Ecosystem Reorganization Index	0.65	2.34	2.68	3.01	3.34	3.65	3.97	Close to 0
Shannon Diversity Index	3.23	3.23	3.23	3.23	3.23	3.23	3.23	High
Change in MTL relative to base	0.02	0.05	0.05	0.06	0.06	0.06	0.06	High MTL

Attributes reflect system conditions at the end of 50-year simulations.

in biomass. We used the Shannon Diversity Index and a biomass-weighted MTL of the foodweb as additional indicators of how changes in cultured geoduck biomass might affect overall foodweb structure. Lower species diversity generally indicates a more stressed ecosystem as species dominance increases and functional redundancy decreases (Odum, 1985). Lower MTL indicates shorter food chains and a more stressed foodweb due to reduced energy flow at higher trophic levels and/or greater sensitivity of predators to stress (Odum, 1985). The Mixed Trophic Impact (m_{ij}) quantifies the direct and indirect impacts of (impacting) group i on (impacted) group j across all trophic pathways that link the two groups, as calculated in Ecopath with Ecosim software. The index does not include connections via mediation functions and thus does not represent non-trophic interactions. We calculated the cumulative Mixed Trophic Impact (ε_i) to determine the net influence of each functional group on the foodweb following Libralato *et al.* (2006):

$$\varepsilon_i = \sqrt{\sum_{j \neq i}^{n} m_{ij}^2} \tag{6}$$

We evaluated the trophic and non-trophic effects of adding cultured geoduck to central Puget Sound by creating three versions of the model: (i) current (low) level of cultured geoducks (base model), (ii) 120% cultured geoduck biomass but no geoduck mediation functions (i.e. trophic effects only); and (iii) 120% cultured geoduck biomass with geoduck mediation functions (i.e. trophic and non-trophic effects). To perturb the foodweb, we forced an increase in cultured geoduck biomass and associated landings by 120% over 50 years. A 120% increase represented a realistic level of increase in geoduck aquaculture and was a large enough perturbation to allow us to examine changes across multiple trophic levels, habitats, and life histories (e.g. birds, pelagic fish, demersal fish, and invertebrates). We compared functional group biomass predictions from the base model (low cultured geoduck biomass) with those from the model with 120% cultured geoduck biomass and no geoduck mediation effects (trophic effects only), as well as the model with 120% cultured geoduck biomass with geoduck mediation functions (trophic and non-trophic effects) to determine the ecological impacts of expanding geoduck aquaculture. We calculated the per cent change in the relative biomass of each functional group in year 50. We then ran the 50-year simulations with individual mediation functions turned off to determine their specific effects on the target functional group as well as their impact on other trophically linked functional groups in the foodweb. Finally, we ran simulations with only individual mediation functions turned on for demersal fish and small crustaceans to determine their influence throughout the foodweb. These functional groups are important prey for a large portion of the foodweb and are likely to have disproportionate effects on foodweb dynamics.

Results

A 120% increase in cultured geoduck biomass had a limited impact on phytoplankton biomass and measures of ecological resilience. The current cultured geoduck standing stock is ~0.1% of the estimated ecological carrying capacity in central Puget Sound (5928 t km^{-2}). At this threshold, the ecotrophic efficiency of phytoplankton exceeded a value of 1, due to grazing mortality exceeding total phytoplankton productivity. As cultured geoduck biomass approached 120% of its initial level, the Ecosystem Reorganization Index diverged from 0 by a small amount indicating a slight reduction in stability, the MTL slightly increased, indicating increased stability, and the Shannon Diversity Index remained constant (Table 3). The Mixed Trophic Impact was very low for cultured geoduck (ranking in the bottom 10 of all 79 functional groups; Supplementary Table S3).

The addition of cultured geoducks into the central Puget Sound foodweb without any mediation functions had very little impact on the simulated biomasses of other functional groups (Supplementary Table S4). That is, after increasing the geoduck biomass by 120% over 50 years, the direct trophic effect of geoduck as a grazer on phytoplankton and as prey resource to other species was nearly negligible. The biomass densities of two geoduck predator groups, sea stars and age 4+ Dungeness crabs (*Cancer magister*), increased by 2% whereas all other functional groups varied by <1% (Supplementary Table S4). The low Mixed Trophic Impact values for cultured geoduck further support these results (Supplementary Table S3).

In contrast, the addition of cultured geoduck mediation functions had a notable impact on the foodweb (Figure 2 and Supplementary Table S4). The biomass of functional groups that were linked to geoduck culture through mediation functions changed considerably, with the biomass densities of some groups increasing and decreasing by over 20% (e.g. surfperch, small crabs, predatory gastropods, and small mouth flatfish; Figure 2). In addition, changes in the biomass of functional groups directly linked to geoduck culture, propagated through the foodweb, contributing to additional changes to biomass in other groups (Figure 2 and Supplementary Table S4).

In total, the biomasses of 9 of the 10 functional groups with cultured geoduck mediation functions changed substantially and were among the top 20 groups demonstrating the greatest change in biomass (Figure 2). Red rock crab was the one exception, which showed <1% change in biomass and had a negative trend despite a positive mediation function (Supplementary Table S4). Small crab biomass increased as a direct effect of their targeted mediation function and decreased without it (Figure 2).

Geoduck mediation functions linked to demersal fish and small crustaceans had substantial effects on the foodweb (Figure 3), supported by the high cumulative Mixed Trophic Impact values for demersal fish and small crustaceans (ranked 11th and 25th of 79 functional groups; Supplementary Table S3). For example, the cultured geoduck–demersal fish mediation function resulted in decreases in herons (−23%) and resident birds (−17%), and

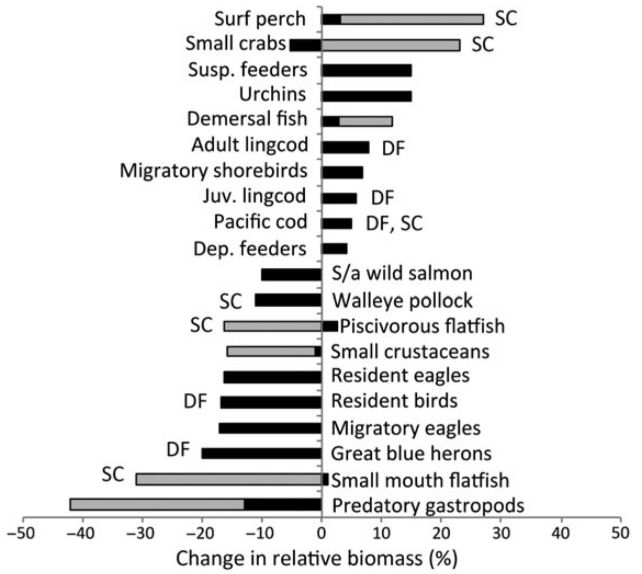

Figure 2. Functional groups with the greatest change in relative biomass between initial conditions and a simulated 120% increase in geoduck biomass over 50 years. Changes in biomass resulting from targeted mediation effects (grey) or trophic connections to groups targeted by mediation effects (black) are indicated. For all but "small crabs", effects are additive. The labels DF (demersal fish) and SC (small crustaceans) denote if those groups are one of their top three prey (as defined by Ecosim). Relative changes in biomass for all foodweb members are in Supplementary Table S2.

increases in Pacific cod (*Gadus macrocephalus*; +7%) and harbour seals (*Phoca vitulina*; +7%; Figure 3). The cultured geoduck–small crustacean mediation functions resulted in reductions in the biomasses of juvenile wild salmon (−7%) and juvenile hatchery salmon (−4%).

Discussion

Foodweb models focused on evaluating the ecological effects of aquaculture have largely neglected non-trophic effects. Our analysis demonstrates the importance of including non-trophic interactions when evaluating the ecological effects of shellfish aquaculture. Accounting for trophic and non-trophic interactions, we demonstrate that the central Puget Sound foodweb can support an increase in geoduck aquaculture with limited changes in individual species' biomass and ecosystem resilience at a basin scale. We also identified several functional groups that may be substantially affected by increased geoduck culture. In contrast, models with only trophic effects of cultured geoduck predicted negligible changes in biomass for functional groups due to geoduck aquaculture.

Habitat modification and facilitation are the predominant ecological effects of geoduck aquaculture in a highly productive system such as central Puget Sound. The trophic impacts of cultured geoducks as both grazer and prey were not influential at the system level. Cultured geoducks did not substantially reduce the availability of phytoplankton for other species, as demonstrated by the small impact on ecological carrying capacity. In addition, geoduck predators (moon snails, starfish, flatfish, red rock crab, and seabirds) are all generalists to varying degrees and showed a limited change in biomass in response to increased geoduck aquaculture. The impact of anti-predator structure (PVC tubes and nets) placed on geoduck plots, however, had a larger influence on the surrounding foodweb by providing predation refuge or by changing foraging opportunities. In turn, these effects propagated throughout the foodweb. The ecological effects of aquaculture structure and habitat modification have been observed for other bivalve species in a range of systems [reviewed in Coen *et al.* (2011)]. Pacific oyster on-bottom culture may reduce eelgrass densities, blade size, and growth rates (Dumbauld *et al.*, 2009; Tallis *et al.*, 2009) and mudflat graveling for clam cultivation may alter benthic community composition (Thom *et al.*, 1994; Simenstad and Fresh, 1995). We suggest that efforts to understand the ecological effects of shellfish aquaculture in productive systems should go beyond modelling the direct trophic effects of bivalves and incorporate non-trophic information when possible. In addition, empirical research is required to determine the functional form and strength of these non-trophic interactions to better determine their influence on the surrounding community (Harvey, 2014).

Functional groups sensitive to changes in increased geoduck aquaculture represent various habitats, trophic levels, and life histories, and are candidate indicators for environmental impacts of increased bivalve aquaculture (e.g. Samhouri *et al.*, 2009). Notably, these species were only sensitive to changes in cultured geoduck with the inclusion of non-trophic mediation effects. Some of these groups (birds, salmon, and benthic fish) are already represented in existing and suggested indicator lists of ecosystem health for Puget Sound (Kershner *et al.*, 2011; Puget Sound Partnership, 2013; Harvey *et al.*, 2014), partly due to the existence of ongoing monitoring programmes. Other species sensitive to geoduck culture (nearshore demersal fish, small crustaceans, and flatfish) are less consistently sampled in the region, but may also prove informative as indicators. Our indicators of ecosystem structure and function (MTL, Shannon Biodiversity Index, Ecosystem Reorganization Index, and Mixed Trophic Impact) did not show conclusive trends, implying that the effects of geoduck culture may be more influential at the species vs. the system level. Additional diet, life history, and aquaculture interaction data for nearshore, demersal fish, small crustaceans, and various bird groups would improve our model and further refine the list of candidate ecosystem indicators for geoduck aquaculture.

The demersal fish and small crustacean functional groups were sensitive to increased cultured geoduck biomass and subsequently influenced biomass changes throughout the foodweb. Their substantial bottom-up influence is due to the aggregation of multiple key prey species into single functional groups, and their multiple trophic connections across the foodweb. The demersal fish community (e.g. poachers, eelpouts, and sculpins) is one of the most diverse and abundant in Puget Sound; however, relatively little is known of their biomass, diet, and life history (Reum and Essington, 2008; Harvey *et al.*, 2012b). In the model, the demersal fish benefit from predator refuge provided by the anti-predation structure on geoduck farms, allowing their population to increase while other predator populations (e.g. seabirds) decreased due to the lack of prey availability. Small crustaceans are one of the most important functional groups in the system, supporting the most bird groups, fish groups, and certain invertebrates (e.g. shrimp, octopuses, age 0+ *Cancer* crabs, and sea stars; Harvey *et al.*, 2012b). This group is one of the seven functional groups that comprise 68% of the total biomass in the foodweb (Harvey *et al.*, 2012b). The small crustaceans experienced a net decrease in biomass as cultured geoduck biomass increased, due to a negative interaction with anti-predation structure associated with cultured geoducks (although they

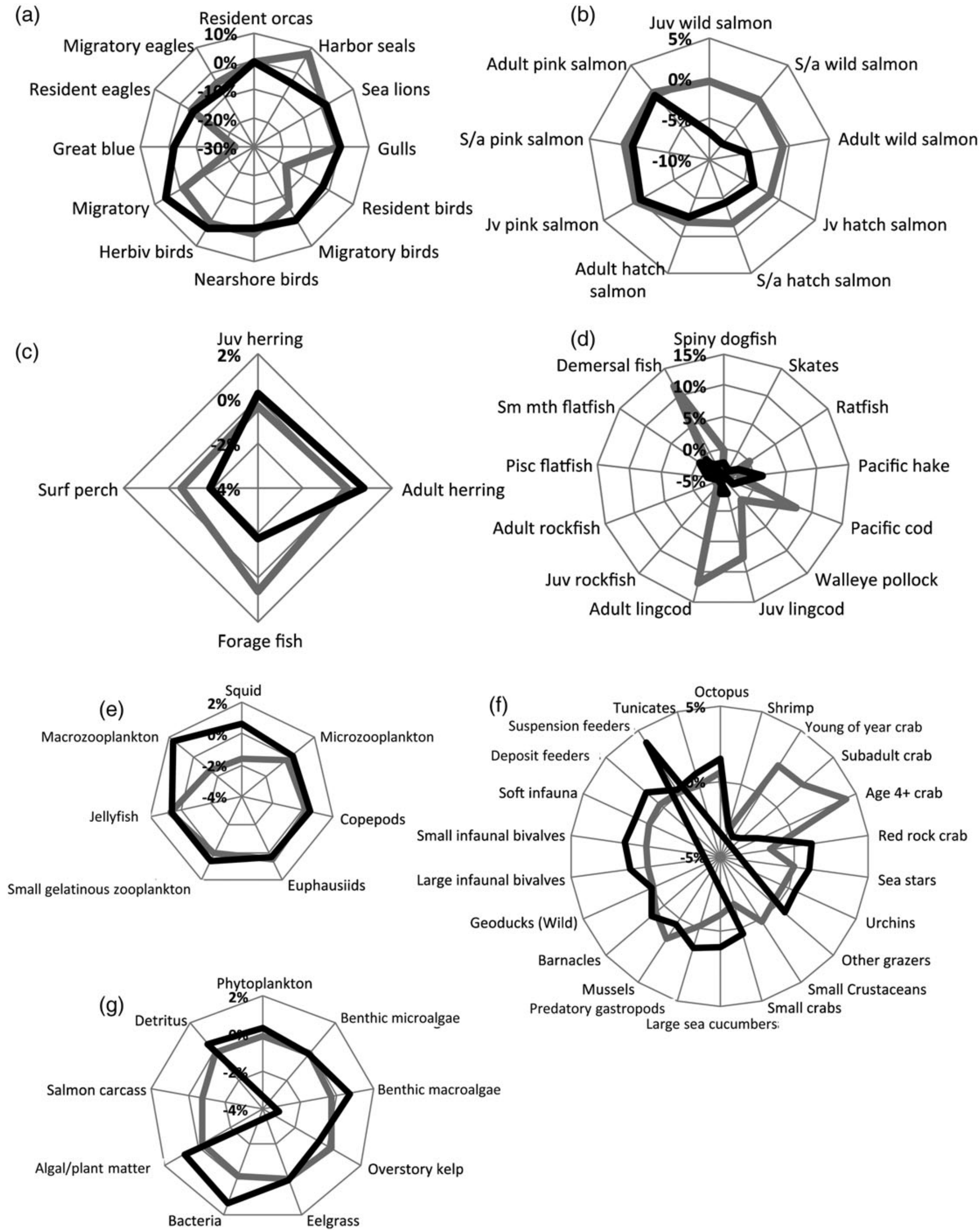

Figure 3. Per cent change in relative biomass due to the addition of individual geoduck mediation effects (see Table 2 for details) on demersal fish (grey lines) and small crustaceans (black). Foodweb groups are divided according to: (a) marine mammals and birds, (b) salmon, (c) pelagic vertebrates, (d) benthic vertebrates, (e) pelagic invertebrates, (f) benthic invertebrates, and (g) primary producers, microbial, and detrital groups.

responded positively to the harvest stage) and potentially due to an increase in predation (e.g. by surfperch and small crabs). Obtaining additional biomass, diet, and life history data and creating species-specific functional groups for demersal fish and small crustaceans would clarify the trophic linkages responding directly to changes in cultured geoduck biomass.

The substantial decrease of most bird groups in the model is important to note, as these are important ecologically, culturally, and socio-economically. A decrease in eagle populations as cultured geoducks increase should benefit other bird groups through release from predation (Harvey *et al.*, 2012b). The biomass of other birds decrease, however, implying bottom-up control in that they have reduced access to key prey (e.g. demersal fish and small crustaceans) due to the predator refuge provided by anti-predator nets on geoduck farms. Migratory shore birds (biomass increase) do not primarily prey upon demersal fish and small crustaceans, and are likely benefiting from a release of eagle predation while not suffering prey depletion. Limited empirical studies have shown both negative and positive interactions between bivalve aquaculture and marine birds (Kelly *et al.*, 1996; Connolly and Colwell, 2005; Zydelis *et al.*, 2009; Coen *et al.*, 2011) in other systems, suggesting that some interactions are likely. Further empirical study is required to understand the relationship between shellfish aquaculture and birds, and validate these results.

Mediation functions in Ecosim are an important tool for incorporating non-trophic interactions into foodweb models, and can help improve their utility in supporting ecosystem approaches to aquaculture. Although mediation functions can help incorporate habitat-specific patterns in the model, they are not equivalent to spatially explicit models (e.g. Atlantis or Ecospace; Fulton *et al.*, 2004a, b; Walters *et al.*, 2010) and are unable to address such issues as the spatial scale of influence of geoduck farms and local community effects. For instance, shifts in the biomass of the subtidal walleye pollock (*Gadus chalcogrammus*) and Pacific cod in response to increased cultured geoduck are most likely due to the model assumptions that demersal fish and small crustaceans are basin-wide, continuous populations. Spatial resolution can enhance model performance (Fulton *et al.*, 2003, 2004c; Gruss *et al.*, 2014), but may also increase uncertainty in model predictions due to limited habitat data. The incorporation of mediation functions into spatial versions of EwE (i.e. Ecospace) offers a promising area of future research as it could enable evaluation of spatially explicit aquaculture development scenarios.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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