GEODUCK AQUACULTURE DEVELOPMENT IN NORTH AMERICA: HOW FAR ALONG ARE WE?

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Geoduck clams are the largest of all deep-burrowing saltwater bivalves. This kind of giant clam is found in a limited number of countries, including the USA, Canada, Mexico, Argentina, Japan, Korea, Italy, Spain and New Zealand (Leyva-Valencia *et al*. 2015, Shamshak and King 2015). These clams are highly esteemed in Asian seafood markets due to their sweet taste and crunchy texture (Fig. 1). Markets for geoduck are mainly in China (including Hong Kong) and Taiwan, but also in Japan, South Korea, Singapore, Malaysia, Vietnam, Portugal, Canada and the USA (Cap Log Group 2013). About 90 percent of the geoduck harvested in North America are exported live to Asia, where they can sell for as much as US$150/lb (Shamshak and King 2015). The market in Asia is largely a high-end restaurant market. They are served in a fondue-style hot pot in China, raw or cooked at sushi restaurants in Japan and in soups and stews in Korea. The demand for geoduck is expected to remain strong as the Asian economy expands. Geoduck comes at a high price, the sought-after delicacy is sold in Canada and US markets for around US$19/lb (Fig. 2).


FIGURE 1. *The Pacific geoduck clam* Panopea generosa.

Due to their high value and demand, the geoduck fishery and aquaculture have thus become lucrative industries in many parts of the world. Currently about ten species are found in worldwide temperate to subtropical seas and five of these are the subject of commercial fishing activities. Research on fisheries management and aquaculture development for this animal is being undertaken in various locations (Table 1). This article summarizes the available information on geoduck aquaculture from published technical reports, articles, and experience gained during collaborative work with the shellfish industries of North America.

GEODUCK FISHERIES

"Geoduck" comes from the Native American word "gooeyduck" meaning "dig deep." The clam has been harvested recreationally in the Pacific Northwest coast for decades, but commercial harvest did not begin until 1970. Commercial fisheries of the Pacific geoduck *Panopea generosa* have operated in Washington State, US and British Columbia (BC), Canada since 1970 (Goodwin and Pease 1989, DFO 17). The southeast

TABLE 1. RECOGNIZED GEODUCK *PANOPEA* SPECIES IN THE WORLD.

Scientific name	*Common/Local name*	*Distribution*	*Research*
Panopea generosa	Pacific geoduck	Southern Alaska to Mexico	Fisheries and aquaculture
Panopea globosa	Cortes geoduck	Gulf of California, Mexico	Fisheries and aquaculture
Panopea bitruncata	Geoduck	Northern Carolina to the Gulf of Mexico	-
Panopea abbrevieta	Geoduck	Southwestern Argentina	Fisheries
Panopea zelandica	King clam	New Zealand	Fisheries and aquaculture
Panopea smithae	King clam	New Zealand	-
Panopea australis	Geoduck/King clam	Southern and Eastern Australia	-
Panopea japonica	Mirugai	Japan Sea	Aquaculture and fisheries
Panopea glycimeris	Geoduck	Northwestern Spain; Mediterranean Sea to South Africa	-

Sources: Leyva-Valencia et al. *2015, Shamshak and King 2015.*

FIGURE 2. *Geoduck clams in a supermarket in Vancouver, Canada.*

FIGURE 3. *Harvested broodstock of Pacific geoduck.*

FIGURE 4. *Harvested broodstock of Cortes geoduck.*

Alaskan Pacific geoduck fishery has expanded greatly since its opening in 1983 (Brickey *et al*. 2012). In Mexico the fishery is even more recent, beginning in 2000, and various surveys suggest that fishermen are harvesting two distinct species of geoduck (*P. generosa* and *P. globosa*) from both coasts of Baja California, Mexico (Pérez-Valencia and Aragón-Noriega, 2013). Geoduck harvesting in Washington State (US) and BC (Canada) has been an US$80 million industry in recent years (Washington Sea Grant 2013). In Mexico, the gross income from geoduck is estimated to be between US$18-30 million (Aragón-Noriega *et al*. 2012, Ferreia-Arrieta *et al*. 2015).

GEODUCK AQUACULTURE

The recent rapid increase in demand for geoduck has resulted in increased pressure on wild populations, prompting aquaculture research and development of this clam. Geoduck aquaculture is very much in its infancy in North America. Farming of the targeted species began on a trial and error basis, with very little help from rigorous scientific research and extension. Knowledge of the biological and ecological characteristics of the geoduck life cycle, especially during larval and juvenile stages, is essential to design aquaculture strategies.

There are two species of geoduck of aquaculture interest in North America – the Pacific geoduck and the Cortes geoduck *Panopea globosa* (Figs. 3 and 4). For Pacific geoduck aquaculture, development initiatives have been implemented in the USA, Canada and Mexico. For Cortes geoduck, aquaculture has been undertaken only in Mexico. The life cycles of these two species are similar, although their geographic distribution limits are not the same (Pérez-Valencia and Aragón-Noriega 2013).

GEODUCK SEED PRODUCTION

Historically aquaculture development of any new species initially depends on collection of seed or juveniles from wild sources. For example, aquaculture of oysters and mussels started with wild-source seed and then various techniques were developed over time to capture wild spat. Spat collected from the wild have usually passed the most critical stages of their life cycle when mortality is highest and have good survival rates when stocked into culture facilities. But collection of wild spat of geoduck is not feasible or practical. Unlike oysters or mussels, geoduck post-larvae (juveniles) burrow into the ocean bottom, making it difficult to collect from wild sources. Also, heterogenous distribution and variable recruitment limit the opportunity to collect wild-source larvae or juveniles. Hatchery production technology is the only viable option to procure a sufficient number of seed for aquaculture development of this species (Marshall 2012).

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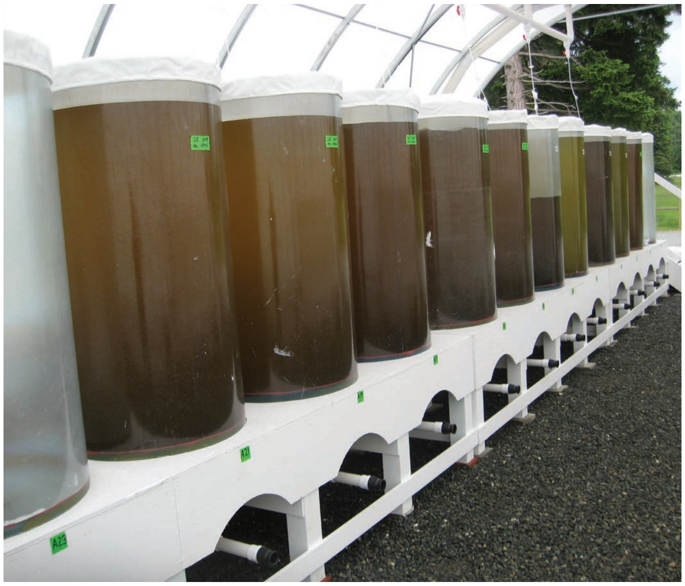

FIGURE 5. *Microalgae tanks for a geoduck hatchery operation.*

In geoduck hatchery systems, broodstock collection, conditioning, spawning induction, knowledge of time to metamorphosis and settlement and algae culture techniques are like a steeplechase race with many obstacles that the hatchery operator must overcome to win. A fair amount of research has been done on geoduck reproductive biology, larvae and juveniles culture in North America (Marshall 2012, Ferreira-Arrieta *et al*. 2015, Liu *et al*. 2017) but very little of this research has been done in a proper pilot-scale or commercial-scale hatchery setting. Seed or spat for geoduck aquaculture development or fishery enhancement in North America are currently produced by only few dedicated small-scale hatcheries, including Taylor Shellfish (Washington State), Alutiiq Pride, OceansAlaska (Alaska), Manatee Holdings, Island Scallop (BC) and Laboratorio Oceanica (Baja California).

Geoduck clams follow a simple annual reproductive cycle. In the natural environment, gametogenesis begins in September and spawning occurs from March to July but sperm or eggs can be found in the gonads of some adults during any time of the year (Sloan and Robinson 1984). For hatchery operation, adults (broodstock) are collected from wild sources from October through December. Prior to collecting broodstock, operators need to obtain a permit or certification from relevant regulatory agencies. In the USA, the fishery is jointly regulated by the Department of Natural Resources, Department of Fish and Wildlife and local Native American tribes. The Department of Fisheries and Oceans (DFO) is the main regulatory agency for the Canadian geoduck fishery and the Mexican fishery is managed by SAGARPA-CONAPESCA (Shamshak and King 2015).

Broodstock Conditioning and Spawning

After wild collection, broodstock need to be conditioned in a controlled environment, including optimum water temperature, salinity and feeding with cultured microalgae. To be used as a diet, microalgae has to meet various criteria, such as ease of culture, high nutritional value with the correct cell size, shape and digestible cell wall to make nutrients available for different life stages (Patil *et al*. 2005). In practice, hatchery operators use a combination of different algal species that provide balanced nutrition and good growth and survival. The most frequently used algal genera in geoduck hatcheries are *Isochrysis*, *Chaetoceros, Phaeodactylum* and *Skeletonema* (Fig. 5). Lack of experienced and skilled technicians or algologists hinders algae culture as well as quality diet production in geoduck hatchery systems in North America.

FIGURE 6. *Downwellers for larval geoduck settlement.*

In most hatcheries in North America, induction of geoduck spawning is conducted from November through early January. Spawning is triggered primarily by an increase in water temperature and the addition of cultured algae to the spawning tank. Broodstock are held in a spawning tank at 13-15 C and then water temperature is increased slightly while adding algal cells to the influent water. Generally, a male spawns first which then triggers spawning in other males and females. Usually relatively few females release eggs during a spawning event. Geoduck females have huge ovaries that contain 10-20 million eggs. Because they are partial spawners, a female will release about 1-2 million eggs during each spawning event (Goodwin and Pease 1989). Eggs and sperm are released into the water where fertilization occurs. However, spawning induction is only the beginning and hatchery operators need to provide a lot of attention and effort during the larval rearing period. Specialized training and observational skills are required to rear the resulting larvae successfully to obtain a sufficient number of juveniles.

Larval Rearing

Fertilized eggs hatch within 2-3 days, depending on rearing temperature. In North America, most shellfish hatchery operators

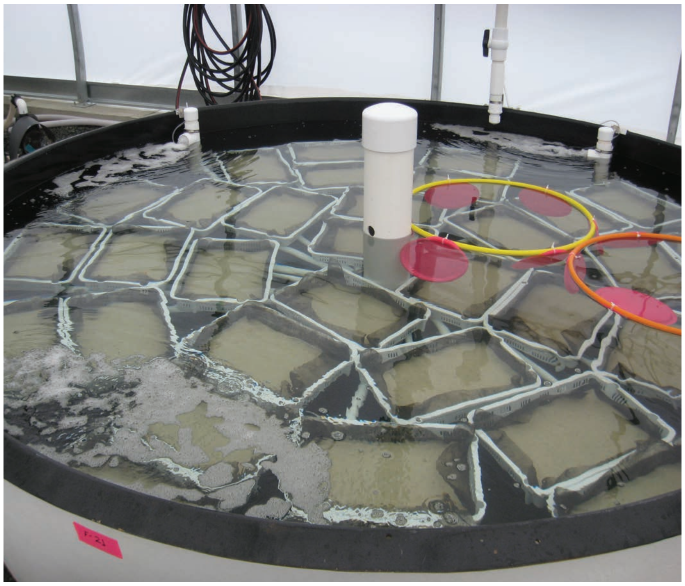

FIGURE 7. *Trays with fine sand substrate for post-settled juveniles.*

use cylindrical cone-bottom fiberglass tanks for larvae culture. Planktonic swimming larvae pass through different stages over 20-25 days before becoming competent for metamorphosis. Competent larvae are then moved into downwellers for settlement (Fig. 6). Metamorphosis and settlement are critical events in the life cycle, marking a fundamental change of lifestyle from a planktonic existence in the water column to an increasingly sessile life on the bottom. Massive mortality of larvae can occur at this stage.

Larvae become post-larvae or spat within 4-5 weeks and then are capable of active crawling along the bottom of culture vessels. In natural environments, post-larvae crawl along the sandy seabed and can dig into the substrate with its foot. They are also capable of attaching themselves to the substrate. During this stage, geoduck juveniles need clean substrates and good water flow. Hatchery operators in North America use various sandy substrates for post-larvae culture and development (Fig. 7). The duration of post-larval stages is 4-5 weeks under hatchery conditions (Goodwin and Pease 1989).

Nursery Culture

When siphon formation is complete and shell length (SL) is around 1 mm, operators transfer juveniles from land-based hatcheries to natural, sea-based secondary nursery systems. The requirement for large quantities of microalgae or to minimize the higher labor cost for a planting-size juvenile (8-10 mm SL) resulted in a shift from land-based to natural sea-based nurseries.

Growing spat in raft-based floating upwelling systems (e.g. FLUPSY) is one of the most popular techniques for geoduck seed production in natural seawater environments. Some hatchery operators use double-layer bag nets in the sub-tidal seabed called "bags in the bottom" (BIBs) to produce planting-size juveniles. BIBs or FLUPSY systems for seed production are relatively successful but poor survival rates limit the supply of large seed.

Protection of geoduck seed from predators is always a challenge in the operation of juvenile production systems. Juvenile geoduck clams are extremely vulnerable to epibenthic predators until they attain a spatial (depth) refuge. Unlike other bivalves, the siphon of geoducks is too long to retract into the shells (Fig. 8), thus they are more vulnerable to predation in a natural seabed environment (Liu *et. al* 2017). Bottom-feeding fish, crabs, sea stars and flat worms are the most common predators of juvenile geoduck smaller than 20 mm SL.

FIGURE 8. *Juvenile geoduck clams ready for out-planting.*

Grow-out

The planting of hatchery-raised seed into a farming area was first piloted by the Washington Department of Fish and Wildlife (WDFW) in the late-1970s. Planting practices initially consisted of broadcasting seed (8 mm SL) from the stern of a slow-moving vessel in shallow water adjacent to selected public beaches. The WDFW has since incorporated intertidal geoduck culture into shellfish enhancement programs. As unprotected juveniles are vulnerable to predation, WDFW gradually changed the planting technique to mesh-covered PVC tubes that proved to be successful in reducing predation. Washington State is now the world's largest producer of farmed geoduck, with nearly 673 t having a total value of US$28 million in 2013 (Seafood Watch 2016). In addition, the US National Oceanic and Atmospheric Administration is working with local industries, including Taylor Shellfish and other state agencies through the Sea Grant program to develop a more efficient network for shellfish aquaculture development, including for geoduck.

British Columbia began experiments in geoduck farming in subtidal environment in the 1990s. In 1996, a DFO/provincial pilot program for geoduck aquaculture research and development was approved in BC with the establishment of five subtidal aquaculture sites (DFO 2014, DFO 2017). The Underwater Harvesters Association, in conjunction with Island Scallop, Manatee Holdings and FAN Seafoods, undertook initial hatchery and seeding efforts in BC. Sections of the Strait of Georgia have been seeded with geoduck using an underwater planting device with varying success. BC is a comparatively small but growing producer of farmed geoduck, with total production about 75 t having a value of $2.4 million in farm gate sales (GSGislason and Associates 2012, Seafood Watch 2016).

More recently, geoduck farming in coastal shoreline areas has been expanded in Alaska and Baja California with modern techniques. Farmers are using PVC tubes that are inserted into the substrate to protect out-planted geoduck seed. The PVC tubes are

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covered with individual nets or collectively with a canopy net to provide further protection against predation. When clams reached a size at which refuge against predation is no longer needed, the PVC tubes and predator netting are removed. There is continued interest and efforts in geoduck aquaculture development in Alaska and Baja California, but with low measurable output.

CHALLENGES

Unlike finfish or other shellfish, geoduck farming may be more difficult due to slow growth of the clam; the grow-out period for hatchery-seeded geoduck is 7-10 years (DFO 2017). Given the long production period, geoduck aquaculture operations require significant investment in terms of capital, planning and management before any return on investment.

In addition to biological and ecological challenges, there are legal and social constraints. In the US and Mexico, the use of intertidal and subtidal benthic plots for geoduck aquaculture is restricted and regulated by the Washington Department of Ecology's Shoreline Master Plans in Washington State and by the Mexican fisheries authority (CONAPESCA) in Baja California. In BC, farming of geoduck is allowed only in the Strait of Georgia. Moreover, most aquaculture tenure agreements stipulate that geoduck farms must maintain a minimum distance of 9 m from eelgrass beds to avoid sedimentation and destruction of eelgrass habitat.

The social challenges of geoduck farming are derived from neighboring inhabitants and various interest groups. Human populations tend to concentrate along the shoreline and coastal shoreline property has high value. These neighboring communities are very concerned about pristine waterfront and aesthetic views (Ryan *et al*. 2017). There have been lawsuits by groups opposing geoduck aquaculture over concerns about potential environmental impacts. Furthermore, coastal communities, especially local First Nations or native tribes deserve a stake in development of their traditional territories. As development of geoduck aquaculture is relatively recent, farming groups are at a disadvantaged position in competing with other interest groups, including housing, boating or mineral exploitation. For example, the Comox Valley waterfront is a potential breeding and nursery ground for geoduck clams that has been occupied by a marina.

The permitting process for geoduck aquaculture is also extensive. For example, in Washington State as many as 11 federal, state, tribal, and local agencies are involved in the permitting process for a single farm that may take years of time and thousands of dollars of investment (Ryan *et al*. 2017). However, unlike salmon or shrimp, farming of geoduck does not require any external feed or chemicals, depending only on primary productivity and seston. It is a native species in North America and various studies suggest that geoduck aquaculture has no or only minor impact on the surrounding environment (Liu *et al*. 2015, Seafood Watch 2016).

REALIZING POTENTIAL

In conclusion, despite its huge potential and significant interest, geoduck aquaculture production is lagging in North America. The following efforts could help realize the full potential of geoduck aquaculture development:

- Research organizations should work collaboratively with the shellfish industry to find possible solutions to industry-identified technical problems, including technology development for quality seed production. The study should be conducted at a pilot-scale shellfish research hatchery so that potential operators can get hands-on experience and share their knowledge on hatchery production techniques.
- Policy and regulatory officials should come forward to play a proactive strategic role in the permitting process and to identify or allocate special zones for geoduck aquaculture development. Federal and local government should offer stimulation and subsidy packages to implement various outreach programs on geoduck aquaculture.
- Conventional aquaculture is often criticized for causing environmental degradation. Aquaculture industry organizations, including growers associations, should arrange result demonstration programs on geoduck aquaculture or water gardening to minimize negative public perceptions.

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Notes

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References

Aragón-Noriega, E.A., E. Alcántara-Razo, L.E. Calderon-Aguilera, and R. Sánchez-Fourcade. 2012. Status of geoduck clam fisheries in Mexico. Journal of Shellfish Research 31:733-738.

Brickey, S., S. Kurlan, M. Miller, T. Monkman, and E. Roemeling. 2012. Comprehensive management of the wild commercial harvest and mariculture of geoduck clams (*Panopea generosa*) in Southeast Alaska. 20 pp.

Cap Log Group. 2013. A value chain analysis of Mexico's emerging commercial geoduck trade. Prepared for Environmental Defense Fund, Mexico. https://www.caploggroup.com/projects

DFO (Department of Fisheries and Oceans Canada). 2014. Review of geoduck hatchery protocols currently in place for the Strait of Georgia and evaluation of potential application to other coastal areas in British Columbia. DFO Can Sci. Advis. Sec. Sci. Advis. Rep. 2014/010.

DFO (Department of Fisheries and Oceans Canada). 2017. Integrated Geoduck Management Framework- Pacific Region. 2017.

Ferreira-Arrieta, A., Z. García-Esquivel, M.A. González-Gómez and E. Valenzuela-Espinoza. 2015. Growth, survival, and feeding rates for the geoduck (*Panopea globosa*) during larval development. Journal of Shellfish Research 34:55-61.

Goodwin, C.L. and B. Pease. 1989. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest) - Pacific Geoduck Clam. United

States of Fish and Wildlife Service. Biological Report. 82, 14.

GSGislason and Associates, Ltd. 2012. The Market for Geoduck. Prepared for Fisheries and Oceans Canada, Vancouver, Canada. 48 pp.

Marshall, R. 2012. Broodstock conditioning and larval rearing of the geoduck clam (*Panopea generosa* Gould, 1850). Ph.D. Dissertation. The University of British Columbia, Vancouver, BC, Canada. 227 pp.

Leyva-Valencia, I., P. Cruz-Hernández, S.T. Álvarez-Castañeda, D.I.Rojas-Posadas, M.M. Correa-Ramírez, B. Vadopalas and D.B. Lluch-Cota. 2015. Phylogeny and Phylogeography of the geoduck *Panopea* (Bivalvia:Hiatellidae). Journal of Shellfish Research 34:11-20.

Liu, W., C.M. Pearce and G. Dovey. 2015. Assessing potential benthic impacts of harvesting the Pacific Geoduck clam in intertidal and subtidal sites in British Columbia, Canada. Journal of Shellfish Research 34 (3):757-775.

Liu W., C.M. Pearce, R.S., McKinley and I.P. Forster. 2017. Effects of sand acclimation on burrowing rate and siphon nipping on growth of juveniles of the Pacific geoduck clam (*Panopea generosa*). Can. Tech. Rep. Fish. Aquat. Sci. 3226: v + 12 pp.

Patil, V., K.I. Reitan, G. Knudsen, L. Mortensen, T. Kallqvist, E. Olsen, G. Vogt and H.R. Gisterod. 2005. Microalgae as source of polyunsaturated fatty acids for aquaculture. Current Topics in Plant Biology 6:57-65.

Pérez-Valencia, S.A. and E.A. Aragón-Noriega. 2013. Age and growth of the Cotes Geoduck *Panopea globosa* (Dall, 1898) in the upper Gulf of California. Indian Journal of Geo-Marine Sciences 42 (2):201-205.

Ryan C.M., P.S. McDonald, D.S. Feinberg, L.W. Hall, J.G. Hamerly and C.W. Wright. 2017. Digging deep: Managing social and policy dimensions of geoduck aquaculture conflict in Puget Sound, Washington. Coastal Management 45(1):73-89.

Seafood Watch. 2016. Seafood Watch Geoduck Report. Farmed Pacific Geoduck Washington State USA and British Columbia Canada. http://seafood.ocean.org/wpcontent/uploads/2016/12/Clams-Farmed-Pacific-Geoduck-Washington-State-USA-and-British-Columbia-Canada-2016.

Shamshak, G.L. and J.R. King. 2015. From cannery to culinary luxury: The evolution of the global geoduck market. Marine Policy 55:81-89.

Sloan, N. K, and S.M.C. Robinson. 1984. Age and gonad development in the geoduck clam *Panope abrupta* (Conrad) from southern British Columbia, Canada. Journal of Shellfish Research 4 (2):131-137.

Washington Sea Grant. 2013. Final Report. Geoduck Aquaculture Research Program. University of Washington, Seattle, WA 98105-6716. https://wsg.washington.edu/wordpress/wpcontent/uploads/publications/Geoduck-Final-Report-Dec-2013.