COMPREHENSIVE LITERATURE REVIEW AND SYNOPSIS OF ISSUES RELATING TO GEODUCK (*PANOPEA ABRUPTA*) ECOLOGY AND AQUACULTURE PRODUCTION

Prepared for

Washington State Department of Natural Resources

by

Kristine Feldman, Brent Vadopalas,
David Armstrong, Carolyn Friedman, Ray Hilborn,
Kerry Naish, Jose Orensanz, and Juan Valero
(School of Aquatic and Fishery Sciences, University of Washington),

Jennifer Ruesink (Department of Biology, University of Washington),

Andrew Suhrbier, Aimee Christy, and Dan Cheney (Pacific Shellfish Institute),

and

Jonathan P. Davis (Baywater Inc.)

February 6, 2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. EXECUTIVE SUMMARY

1.1 General life history

Geoducks (*Panopea abrupta* Conrad) exist in marine and estuarine waters from southeast Alaska to Baja California. Puget Sound and British Columbia contain large numbers of geoducks, and this general region may be considered the geographic center of their known distribution. These large clams are typically found in loose substrates of gravel, sand, and/or mud. Other species of geoducks are found in temperate climes worldwide, from Argentina to New Zealand.

Geoducks are distinctive in a number of ways. Anatomically, they are similar to many clam species. However, geoducks are unable to fully retract their siphon and mantle into their shell, leaving them vulnerable to predation until at a safe burial depth. Their digging appendage, the foot, is vestigial in the adult, rendering the adult geoduck incapable of either digging or righting itself if removed from the protection of the substrate.

Geoducks are also capable of producing large numbers of eggs and sperm. They can produce up to 20 million eggs per spawning, and are capable of spawning multiple times in a hatchery setting. Reproduction is seasonal, and peaks in May-June. Geoducks are also extremely long-lived, and remain able to spawn. Using annuli in the shell, similar to tree rings, age can be accurately estimated. The oldest specimen recorded was 168, and individuals older than 100 years are not uncommon.

As adults, males and females occur in approximately equal numbers. Gametes are released directly into the water, and zygotes develop quickly into swimming larvae. Geoducks remain in this swimming phase, and capable of migration, for up to 47 days before settling and digging into the substrate. The basic timing, temperature, and salinity required for normal larval development in the hatchery have been outlined. The growth rate for geoducks is highest during the first 10 years of life; there is no significant size difference between a 100 and a 20 year-old geoduck.

1.2 Predator-prey interactions

Few studies have qualitatively examined, much less quantified, predator-prey interactions involving the geoduck clam and how they affect the structure of naturally occurring populations. What little field and laboratory research there is, has focused on predation of commercially cultured geoduck seed and the relative success of predator exclusion devices to increase population densities for the benefit of enhancement programs on public lands as well as the aquaculture industry. Juvenile geoducks are most vulnerable to predation for the first year of life. After two years, the majority of clams are buried deep, beyond the foraging range of most predators. Based on dive surveys over planted geoduck beds and results of limited laboratory studies, epibenthic predators of juvenile geoducks in Puget Sound include crabs (*Cancer productus* and *Cancer gracilis*), sea stars (*Pisaster brevispinus* and *Pycnopodia helianthoides*), gastropods (*Polinices lewisii, Natica sp. and Nassarius mendicus*), and flatfishes (*Platichthys stellatus*, *Parophyrs vetulus*, *Lepidopsetta bilineata*, and *Psettichthys melanostictus*). Black scoters (*Melanitta nigra americana*) are suspected but unconfirmed predators of juvenile geoduck seed. No information is available to estimate how much energetic support consumers receive from geoducks versus other food sources. Quantitative data are also needed on the spatial and temporal distributions and densities of geoduck predators and controlled experimentation on factors that affect consumption rates of juvenile clams such as tidal elevation-water depth, predator size, prey size and density, bivalve burial depth, and habitat quality and structure.

1.3 Community and ecosystem effects of geoducks

Geoducks can comprise a substantial portion of infaunal biomass in soft sediments within their range; however, little is known of the community- or ecosystem-level effects of geoducks. Geoducks potentially influence their environment through four linkages: they may alter water properties through suspension feeding; they may alter sediment properties through deposition of pseudofeces and feces; they may alter the physical attributes of their environment (e.g. sediment grain size or stability), and other species may change distribution accordingly (so-called “ecosystem engineering”); and they may provide a prey resource for consumers, influencing consumer dynamics through "bottom-up" processes related to resource supply.

1.4 Spatial structure of geoduck populations

Geoduck density is highly variable in Puget Sound; the greatest average densities occur in the South Sound. Density is also affected by water depth and substrate. The deepest areas (to 18m) and mud-sand and sand substrates contain the highest average densities of geoducks. Geoducks are typically found clustered together. The inclination to aggregate is not well understood, but may be due to substrate type, pheromones, or attraction to other organisms in the area.

The known population size of geoducks also varies by region. Many subtidal acres containing geoducks have been surveyed, mapped, and divided into tracts or beds. South Sound, Central Sound, and Hood Canal have large numbers of geoducks, with less in North Sound and the Strait of Juan de Fuca.

Clams exhibit changes in abundance at different temporal scales. Geoducks, being long-lived, can reproduce and recruit to the adult population successfully only rarely and still maintain population levels. Geoduck age data reveal that some years yielded very large recruitment relative to the rest, suggesting that large changes in abundance may be a natural occurrence.

1.5 Genetic-based differences at the population level

Some marine mollusks exhibit genetic differences between populations, contrary to their ability to disperse as larvae. Puget Sound's complex hydrology may inhibit the dispersal of larvae and the concomitant gene flow. The fecundity, longevity, and relatively long free-swimming larval stage of geoducks, however, may buffer against differentiation.

In a recent study of genetic differentiation at the population level conducted by WDFW and UW, low levels of differentiation between a few collections were found. These differences occurred both within one tract, between collections from sites within Puget Sound, and also between Puget Sound sites and a collection from SE Alaska. However, differences were not discerned in the majority of comparisons between sites.

The biological significance of the detected differences is not apparent, but the differences are probably due neither to reproductive isolation, nor to few successful parents in the population.

To avoid genetic risk to wild populations of geoducks, it may be more effective to reproductively separate cultured animals from the wild than to attempt to culture populations that exhibit the high levels of genetic variability present in wild populations. In geoducks, this may be accomplished by harvest prior to sexual maturity, or possibly by rendering cultured animals functionally sterile.

1.6 Commercial geoduck hatchery practices

Work on geoduck culture commenced over 30 years ago. Much of the pioneering work was done by Washington Department of Fisheries (WDF) personnel, and was adapted from techniques used for other bivalves. Current practices used by Washington State geoduck hatcheries evolved from this early work by WDF.

To avoid genetic risks, broodstock are collected from the same geographic region into which the seed will be outplanted. For several weeks, the broodstock are held at ambient temperature and fed. Broodstock are stimulated to spawn by increasing the water flow, water temperature, and/or food ration. Typically, 5-15 females and an equal number of males are used in each spawning.

Broodstock, larvae and juveniles are fed a diversity of cultured microalgae (single-celled) to ensure adequate nutrition. Some of the long chain fatty acids appear especially important, and algae culture conditions are altered to maximize the nutritional value of the food.

Larvae are produced in 18-19 days in large tanks at densities that decrease over time from 10 to 1 larvae/mL. Water changes occur every 4-5 days, and the larvae are fed twice daily. Once larvae are competent to settle, they are moved into downwellers for several days until metamorphosis has occurred. After metamorphosis, a sand-based nursery system is used to husband large numbers of juvenile clams until large enough to move to tertiary field nursery systems, where they are held until ready to plant in intertidal beds.

Some geoduck culture exists outside the US. British Columbia in particular has been active, with at least three hatcheries historically involved in geoduck seed production. There is continued interest in geoduck culture in China, Argentina, and New Zealand, but with little measurable output.

1.7 Development of aquaculture production systems for cultured geoduck

The Washington Department of Fish and Wildlife (WDFW) has been actively culturing geoducks since the 1970s. Initial seeding trials consisted of scattering small hatchery-reared juveniles onto the subtidal seabed floor. Dive surveys revealed less than 1% of outplanted seed survived; high mortality of unprotected seed was attributed in large part to predation. Subsequently, WDFW experimented with growing outplanted seed in mesh-covered polyvinylchloride (PVC) tubes in intertidal beds and in tree planting cones in subtidal beds. While survival (to age-one) exhibited spatial and temporal variability in these early studies (15-70%), the general technique was deemed successful in reducing intertidal predation. With the success of predator exclusion devices, intertidal geoduck aquaculture has grown in Washington State. WDFW has since incorporated intertidal geoduck culture into their shellfish enhancement program on public beaches, and considerable commercial development has occurred in Washington State and British Columbia, Canada. British Columbia has also developed a subtidal geoduck aquaculture program in which much of the labor involved in planting has been mechanized. The majority of geoduck clams from Washington and British Columbia are exported to Asian markets, but some clams are processed and supplied to local markets for consumption. Outbreaks of Paralytic Shellfish Poisoning (PSP) affect the harvest of geoducks since these filter-feeding bivalves ingest the dinoflagellate *Alexandrium catenella* that produces the toxin. While most of the toxin accumulates in the viscera, this portion is not always discarded prior to processing.

2. GENERAL LIFE HISTORY (UW, Brent Vadopalas)

2.1 Taxonomy (Conrad 1849)

Phylum: Mollusca

Class: Bivalvia

Order: Myoida

Family: Hiatellidae

Genus: Panopea

Species: abrupta

Geoduck clams (*Panopea abrupta*)

2.2 Shell structure and age estimation

Panopea abrupta is a large species, with the valve length of some adult specimens approaching 20 cm (Kozloff 1983). The valve of this species has a broad, continuous pallial line with a short pallial sinus. Inner margins are smooth throughout, one cardinal tooth, external ligament seated on a nymph, porcelaneous interior, adductor scars roughly equal in shape, and a chondrophore. The valve is composed of three layers, the outer two of which reveal seasonal growth patterns in the microstructure upon microscopic examination. These growth patterns were first successfully used to estimate age in geoducks by Shaul and Goodwin (1982) by the acetate peel technique. These and subsequent investigators (e.g. Breen and Shields 1983, Goodwin and Shaul 1984, Sloan and Robinson 1984) used this technique to produce age frequency distributions for Washington State and British Columbia collections. Important to any age estimation technique is verification that the growth patterns tallied are in fact annual. Shaul and Goodwin (1982) conducted two verification experiments. The first examined growth band counts from two groups of geoducks, sampled from and adjacent to a channel that had been dredged 26 years previously. The authors projected that since clams could not have survived the dredging, only those that were sampled from the adjacent areas could exceed 26 years of age. Counts of putative annuli supported their conclusion. However, patchiness in settlement of year classes coupled with spatially and temporally variable recruitment has been observed (Goodwin and Shaul 1984, Vadopalas, unpublished data). Thus, highly variable numbers of successful progeny per year class could yield the observed results.

In the second study, a mark and recapture experiment, the authors marked the shells of 91 clams raised in a hatchery until one year old and then outplanted. After seven years in the substrate, eight growth lines were discerned in each of the three recovered geoducks. This information was used by the authors as confirmation of an apparently annual growth pattern. Using commercially cultured geoducks of known age, we were able to verify in a blind test that clams born 2, 3, and 6 years prior had 2, 3 and 6 growth bands, respectively (Vadopalas, unpublished data). While we can be confident that growth bands are annual during early life based on these results, the decelerated shell and somatic growth after age 10 (Goodwin and Shaul 1984) may cause the growth line periodicity to change.

Radioactive carbon (^{14}C) from atmospheric testing of nuclear weaponry in the 1950s and 1960s established a strong age-dependent signal in carbonaceous materials. Recently, we analyzed ^{14}C levels in a time series of seven samples from geoduck clam valves (Vadopalas and Weidman, unpublished data), and found levels that correspond to the documented rise in atmospheric ^{14}C resulting from the nuclear bomb testing that occurred. The levels correspond well to birth years estimated from growth ring counts, providing further evidence that growth rings in geoduck clams are deposited annually throughout their life history.

Using these age estimation techniques, the oldest geoduck recorded was 146 years old and the oldest reproductive geoduck recorded was 107 years old (Sloan and Robinson 1984). There are unpublished accounts of a Puget Sound geoduck estimated to be 164, and a geoduck from the Queen Charlotte Islands estimated to be 168 years old.

2.3 Anatomy

The interior anatomy of *Panopea abrupta* is similar to other bivalves. The extremely large, fused siphon and mantle that cannot be fully withdrawn distinguishes the geoduck from other clams in the region. The only opening in the mantle is the pedal aperture, a small slit through the mantle located dorsally on the anterior end. The extremely large siphons extend from the posterior end. In situ, the geoduck is oriented with the posterior towards the surface, where seawater containing dissolved oxygen and suspended microalgae is pumped via the ciliated ctenidia, or gills, in through the inhalant siphon. The ctenidia perform gas exchange, and trap, sort, and transport food particles to the labial palps, which are also involved in sorting food particles into the esophagus. Rejected food particles are bound with mucus and periodically ejected as psuedofeces via the exhalant siphon. After entering the esophagus, the mucus-bound particles are transported via cilia to the stomach and crystalline style. The style is a freely rotating gelatinous rod that contains enzymes involved in digestion. The food moves from the stomach to the digestive gland, where most of the intracellular digestion takes place. After digestion, material enters the intestine and is discharged from the anus. Feces are expelled via the exhalant siphon. The gonad surrounds the visceral mass, and depending on season and condition can vary from a few millimeters to over a centimeter thick.

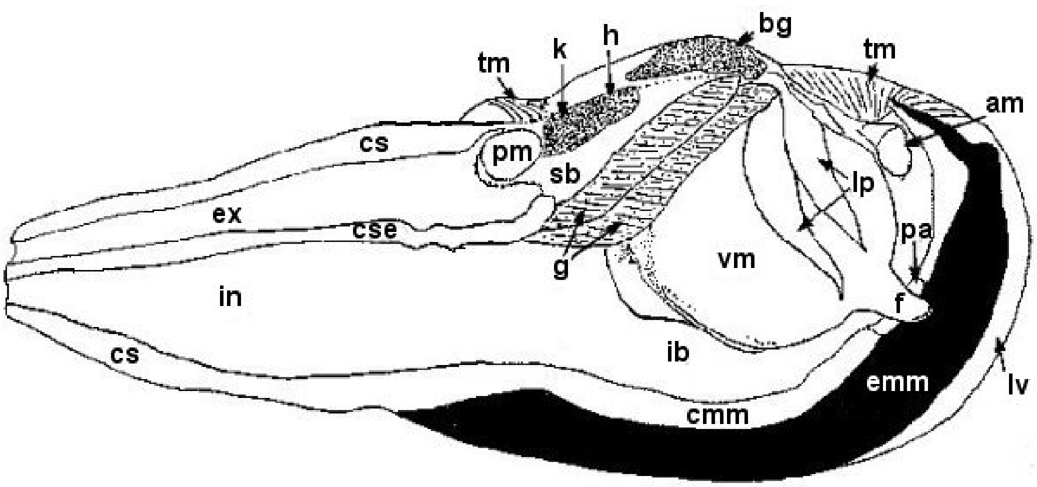


Figure 1. Sketch of the internal organization of the major organs of the geoduck clam, *Panopea abrupta*. The right valve and right side of the muscular mantle and siphon have been dissected away to reveal the fused siphons and the arrangement of the internal organs. The thin mantle (**tm**) that lines the inner surface of the right valve to the pallial line has been turned over the dorsal edge of the left valve (**lv**). Other labels on the sketch are: **am** - anterior adductor muscle, **bg** - brown gland, **cmm** - cut surface of muscular mantle, **cs** - cut surface of siphon, **cse** - cut surface of septum, **emm** - external surface of muscular mantle, **ex** - excurrent channel, **f** - foot, **g** - gills, **h** - heart, **ib** - infrabranchial chamber, **in** - incurrent channel, **k** - kidney, **lp** - labial palps, **lv** - left valve, **pa** - pedal aperture, **pm** - posterior adductor muscle, **sb** - suprabranchial chamber, **tm** - thin mantle, **vm** - visceral mass. Figure and legend from Bower et al. (2003).

2.4 Reproduction

Gametogenesis in geoducks follows an annual cycle, initiating in late summer. Goodwin (1976) observed gametogenesis in 124 geoducks from six locations in Puget Sound and characterized them into five phases of gametogenesis. He found that 50% were in the early active phase in September, with 92% ripe in November. Clams were 100% ripe in May, and by August 50% were spent. Ripe males were found every month collected, from a low of 14% in August to 100% in April. No ripe females were collected, on the other hand, from August-October. In British Columbia, a similar pattern emerged. A total of 624 geoducks were collected from 52 locations (Turner and Cox 1981). By January, 98% of the specimens were in the early active phase, and 91% were ripe in May. Spawning commenced in May, 77% had spawned by June, and 100% were spent by August. Sloan and Robinson (1984) reported similar seasonal changes in gametogenic condition for 365 geoducks from British Columbia, although like

Goodwin's (1976) results, the females exhibited a more contracted spawning season than the males.

Spawning geoducks

2.5 Embryogenesis

Knowledge of reproductive development has been well documented in some bivalve species as reviewed in Sastry (1979). Longo (1987) describes the general meiotic process in clams, using *Spisula solidissima* as an example. Desrosiers et al. (1996) present an analysis of fertilization and meiotic development in the Giant scallop, *Placopecten magellanicus*. Geoducks follow the general pattern of meiotic development

(Vadopalas and Davis unpublished data). Goodwin et al. (1979) detail the post-embryonic developmental stages of the larval geoduck clam. In an earlier study, Goodwin (1973a) described the combined effects of salinity and temperature on the timing of geoduck clam embryonic development. The optimal temperature and salinity ranges reported for embryonic development were 6-16 ºC and 27.5-32.5 ‰, respectively. Outside these ranges there is a significant reduction of normal development from the embryonic to the larval stage (Goodwin 1973b). However, temperature and salinity tolerance can vary between developmental stages in clams (Sastry 1979); larval geoducks have been cultured at temperatures as high as 18 °C and adults inhabit bays that attain summer temperatures in the low 20s.

2.6 Distribution

Naturally occurring populations of various species of *Panopea* clams occur world-wide, including Japan, Argentina, and New Zealand. *P. abrupta*, one of the more massive species in the genus, is reported to occur in coastal waters of the Western Pacific from Baja California to Alaska (Cheney and Mumford 1986, Morris et al. 1980) and in estuarine environments along the west coast of North America and in Japan (Goodwin and Pease 1989). However, this species' range may not extend as far as Japan and Mexico, since the congeners *P. japonica* and *P. globosa,* known to occur in Japan and the Gulf of California respectively, may have been mistakenly identified as *P. abrupta*. To our knowledge, there have been no intentional introductions of *P. abrupta* to other regions. Hereafter referred to as the geoduck clam, *P. abrupta* occur in high abundance in Puget Sound, Washington, where a commercial fishery for subtidal geoducks commenced in 1970 (Goodwin 1973b).

2.7 Habitat

Adults are found in sand, mud, mud-sand, mud-gravel, sand-gravel, and mixed loose substrates. In Puget Sound, geoducks are found contagiously distributed in smaller patches and in beds of high abundance, from the low intertidal to depths of 110 meters or more (Jamison et al. 1984). In Puget Sound, the average geoduck bed density is 2.1 geoducks/m^2 (Goodwin and Pease 1991). Geoducks tend to aggregate within the beds, in clumps containing an average of 109 animals (Goodwin and Pease 1991). Aggregation of pelecypods is, in part, considered important for spawning synchronization (Sastry 1979). Bed density tends to increase with depth to the extent studied (25 meters; Campbell et al. 1998). On the other hand, mean length and weight decrease with depth (Goodwin and Pease 1991). Adult geoducks can tolerate temperatures from 8 °C (Goodwin et al. 1979) to 22 °C (Goodwin and Pease 1989) and salinities down to 25 ‰ (Goodwin 1973b). The upper salinity tolerance may preclude habitation in open ocean environments (Goodwin 1973b) where salinities are typically in excess of 33 ‰. Known geoduck resources in the Strait of Juan de Fuca occur where salinities are typically less than 32 ‰ (Herlinveaux and Tully 1961). Divers have observed geoducks as deep as 60 meters (Goodwin 1973a) where temperatures rarely exceed 10 ºC. Subtidally, however, very little is known of their distribution. Existing evidence of deep water stocks is limited to two pilot studies of a single area in Case Inlet (south Puget Sound). These video surveys revealed what appear to be significant aggregations of geoduck clams below the 18 meter MLLW fishing limit to a depth of 110 meters (Jamison et al. 1984, Goodwin, unpublished data). From these few data, subtidal geoduck abundance in Puget Sound was estimated to be 25,800,000 individuals, based on video reconnaissance (Jamison et al. 1984). Washington Department of Fish and Wildlife (WDFW) and Washington Department of Natural Resources (WDNR) estimate that 50% of the total biomass in the inland waters of Washington is below legally fishable depths (Palazzi et al. 2001). It has been assumed that these deep water stocks contribute to recruitment and recovery of fished areas, yet data are also lacking to support this important assumption.

2.8 Life cycle

Geoducks are dioecious, occur in an approximately 1:1 sex ratio as adults, and are facultative repeat broadcast spawners, at least in the hatchery environment. Fertilization occurs externally: the 80µm oocytes are released into the water column and arrest in the first meiotic prophase (Vadopalas, unpublished data). Synchronization of spawning is not well understood, but the detection of sperm in seawater from one male may cue mass spawning in the aggregation (Sastry 1979). Once fertilization occurs, meiosis progresses through expulsion of both polar bodies. The duration of the meiotic cycle is affected by temperature: at 30 ‰ salinity, meiosis took 106 min. at 11 °C, 78 min. at 15 °C, and 56 min. at 19 °C (Vadopalas, unpublished data). Salinity also affects meiotic duration. At 15 °C, completion of meiosis took 106 min. at 24 ‰, 81 min. at 27 ‰, and 78 min. at 30 ‰ (Vadopalas, unpublished data).

Subsequent to the completion of meiosis in the ova, the male and female pronuclei break down prior to the first mitotic division. Embryonic development requires salinities between 27.5-32.5 ‰ and temperatures between 6-16 °C (Goodwin 1973b). After approximately 48 hours of embryonic development (trochophore stage), the trochophore develops into an actively swimming and feeding veliger larva (straight-hinge or D-stage) (Goodwin et al. 1979). The veliger stage lasts 16-35 days at 16 ºC (Goodwin and Pease 1989), and 47 days at 14 ºC (Goodwin et al. 1979), during which the swimming veliger feeds on microalgae and grows from 111 to 381 μm in shell height (Goodwin et al. 1979). There is a paucity of studies on the swimming behavior of bivalve veliger larvae.

At metamorphosis, larval geoducks develop a foot and are ready to begin transition from a pelagic to a sessile form. During the initial stage of metamorphosis geoducks settle to the bottom, lose their velum, develop primary gill structures (ctenidia), and develop spines on the growing edge of the shell (Goodwin et al. 1979). Over the next six to eight weeks each plantigrade geoduck grows a siphon, completes the formation of the ctenidia, and fuses its mantle. During this stage a geoduck crawls around with its foot and eats by pedal-palp feeding; the foot is used to transfer detrital food to the mouth (King 1986). These postlarvae can anchor themselves to the substrate with byssal threads. Postlarvae can also detach from the substrate, form a byssal 'parachute,' and travel down current (Goodwin and Pease 1989). A current speed of 1 cm/sec is sufficient to suspend bivalve larvae in this manner (Sigurdsson et al. 1976). The post-larval stage lasts two to four weeks under hatchery conditions (Goodwin and Pease 1989). During this pedal-palp feeding stage, cultured geoducks require clean sand or mud-sand substrate and good current flow. When siphon formation is complete, the shell height is between 1.5 and 2 mm. By this time the geoducks have made the transition from pedal-palp feeding to filter feeding (King 1986), are dug into the bottom, and have begun their sedentary existence. Juveniles resemble the adult, and valve length increases approximately 30 mm per year for the first three years (Goodwin 1976).

Geoduck seed clams

Growth, as measured by valve length, is considered greatest up to about age 10; thereafter increases in valve length are reduced. Valves continue to increase in thickness throughout life, enabling age estimation based on shell layers, or annuli, visible in thin sections of the chondrophore (detailed above). Andersen (1971) reported geoducks attain sexual maturity at three years for males and four years for females; Sloan and Robinson (1984) report a minimum age 6 and 7 for mature males and females. The difference may be attributed to either the age estimation techniques employed or latitudinal differences of the samples. Geoducks continue to grow to adult size with an average shell length of 75 mm, and reach a final burial depth of about a meter. Adult geoducks cannot dig and are not mobile. They extend their siphons to the substrate surface for feeding and respiration, and withdraw their siphons for protection against predators. In general, they grow to a harvest size of just under one kilogram in four to six years and to maximum size in about 15 years. They are very long-lived and specimens presumed to be older than 100 years are not uncommon. Individuals as old as 107 years have contained viable gametes; no reproductive senility has been reported (Sloan and Robinson 1984)

3. PREDATOR-PREY INTERACTIONS (UW, Kristine Feldman)

3.1 Introduction

In benthic marine communities, predation has been shown to be a critical determinant in regulating the population dynamics of numerous bivalve species, many of which are of commercial importance. Here we review published research on predator-prey interactions involving the deep-burrowing geoduck clam *Panopea abrupta*. Although *P. abrupta* is unique in its morphological and ecological characteristics, we include data from studies on other infaunal bivalves where they are preyed upon by similar types of predators in order to expand on the breadth of information available with respect to this type of predator-prey relationship. This section on predator-prey dynamics is organized as follows. First, we review predation on different life history stages of *P. abrupta*. Second, we summarize published accounts of predation on hatchery-produced geoduck seed and the development of predator exclusion techniques to improve seed survival. And third, we examine major predators of geoduck clams and other infaunal marine bivalves and factors that affect predator foraging behavior and consumption rates.

3.2 Predation risk and geoduck life history stage

Like most marine invertebrates, *Panopea abrupta* has a complex life cycle in which planktonic larvae are spatially segregated from benthic-dwelling postlarvae, juveniles, and adults. Although no studies have specifically examined predation on geoduck larvae, Goodwin and Pease (1989) suggested that they are likely preyed upon by a multitude of pelagic-feeding fishes, planktonic invertebrates or vertebrates, and suspension-feeding invertebrates. With respect to the latter category, studies have documented ingestion of bivalve larvae by adult conspecifics and other filter feeding bivalves (e.g. Andre et al. 1993, Tamburri and Zimmer-Faust 1996). In addition to *P. abrupta*, other suspension feeding bivalves, such as Horse clams (*Tresus capax* and *Tresus nuttalli*), Butter clams (S*axidomus giganteus*), and Littleneck clams (*Protothaca* *staminea*), are abundant in many benthic habitats of Puget Sound (Goodwin 1979, Goodwin and Pease 1991) and conceivably could ingest planktonic geoduck larvae.

Population-level effects of suspension feeders on bivalve larvae have been difficult to demonstrate or too complex to generalize, however. Some studies have reported negative effects of suspension feeders on bivalve recruitment densities (Andre and Rosenberg 1991, Andre et al. 1993), others little or no effect (Black and Peterson 1988, Ertman and Jumars 1988, Hines et al. 1989), while yet others have reported a positive effect (Ahn et al. 1993). The contagious distribution of geoducks and clustering of juveniles near adults (Goodwin and Shaul 1984) could result from enhanced settlement of larvae in response to adult conspecifics or chemical cues from the biogenic structures of chaetopterid polychaetes commonly associated with geoduck beds (Pease and Cooper 1986). However, other factors such as food supply, fluid dynamics, sediment chemistry, and differential post-settlement mortality (Ertman and Jumars 1988) could also produce observed density-mediated recruitment patterns. Without controlled experimentation, it is unclear how these post-settlement distributions originate.

Juvenile geoduck clams are extremely vulnerable to a suite of epibenthic predators until they attain a spatial (depth) refuge. Once geoducks reach 1.5-2.0 mm shell length (SL) and their siphon is completely formed, they bury into the substrate and begin their final transition to a sedentary existence. For the first several months, juveniles are vertically distributed in the upper few centimeters of sediment in order to maintain contact with the water column. Burial depth is directly related to shell length and siphon length, which has been documented for other species of infaunal bivalves as well (Zwarts and Wanink 1989). As burial depth increases, the risk of predation is reduced. Studies have shown that clams that are buried more deeply have better survival rates (Virnstein 1977, Holland et al. 1980, Sloan and Robinson 1983, Haddon et al. 1987, Zaklan and Ydenberg 1997). For example, Blundon and Kennedy (1982) examined the effects of burial depth of *Mya arenaria* (a soft-shelled, gaping, and deep burrowing bivalve) on predation rates by the blue crab *Callinectes sapidus*. Blue crabs (121-180 mm carapace width, CW) consumed significantly more clams (30-40 mm SL) at 5 and 10 cm depth (4.9 and 4.5 clams/crab/day, respectively) than at 15 and 20 cm depth (2.3 and 0.8 clams/crab/day, respectively). Burial depths used in their experiment corresponded with vertical distributions of *M. arenaria* in field surveys. Goodwin and Pease (1989) reported that one-year old geoduck seed recovered from an outplanted area with high growth averaged 36.6 mm SL (range 28-51 mm) at a mean depth of 33.6 cm (range 23-46 cm). Thus, juvenile geoducks are most vulnerable to predation for the first year of life. After two years, the majority of clams are deeply buried and beyond the foraging range of most predators (Goodwin and Pease 1989).

Adult geoduck clams (75-200+ mm SL; Goodwin and Pease 1989) reach a maximum depth of approximately one meter. Unlike juveniles, they are immobile and no longer capable of digging. Virtually all predation-induced mortality at this size is the result of commercial and sport fisheries. However, predation on adult geoducks by sea stars has been reported in areas where clams were prevented from attaining maximum burial depths due to sedimentary conditions (Sloan and Robinson 1983). In addition, both juveniles and adults are vulnerable to siphon cropping by epibenthic vertebrates and invertebrates, which will be discussed in greater detail in a subsequent subsection. While this may not directly result in death, siphon-cropping has been shown to impact bivalve feeding and growth (Peterson and Quammen 1982, Kamermans and Huitema 1994, Nakaoka 2000).

3.3 Predation on juvenile geoduck clams

Most of the qualitative and quantitative data on predation of juvenile geoducks has resulted from enhancement programs on public lands and private aquaculture in which hatchery-produced seed is outplanted in an effort to increase recreational harvest opportunities as well as harvest of a commercial product. These data have helped improve seed survival in managed habitats and are described in some detail below. Effects of planting practices, seed size and density, and predator exclusion devices however, may alter predator foraging behavior and consumption rates. More studies are needed on the effects of predators on juvenile geoducks in naturally occurring populations.

When WDFW first began outplanting hatchery–produced geoduck seed in the late 1980s, survival was less than 1%, well below their expected return of 5-10% surviving to harvest (Beattie and Blake 1999). High seed mortality was attributed in large part to predation on exposed and shallow-buried clams. Planting practices initially consisted of broadcasting seed (average of 8 mm SL) primarily from the stern of a slow-moving vessel, rendering unprotected juveniles vulnerable to a suite of predators as clams descended through the water column and settled on existing subtidal geoduck beds. Studies have shown that burial time is a function of bivalve size: smaller individuals are capable of burrowing more quickly than larger conspecifics (Tallqvist 2001). Similarly, Goodwin and Pease (1989) found that geoduck seed with a mean shell length of 5 mm took an average of 8 minutes to bury completely, whereas 10 mm clams required an average of 30 minutes. Optimal seed size under this planting scenario is therefore a function of both digging speed and maximum burial depth to minimize losses to epibenthic predators.

Dive surveys coinciding with broadcast seeding trials have documented a number of species feeding on exposed seed, including the sunflower star (*Pycnopodia helianthoides*), lean basket-whelk (*Nassarius mendicus*), coonstripe shrimp (*Pandalus danae*), red rock crab (*Cancer productus*), graceful crab (*Cancer gracilis*), starry flounder (*Platichthys stellatus*), English sole (*Parophyrs vetulus*), rock sole (*Lepidopsetta bilineata*), sand sole (*Psettichthys melanostictus*) and pile perch (*Rhacochilus vacca*) (Goodwin and Pease 1989). With the exception of coonstripe shrimp and pile perch, these species are capable or believed capable of preying on buried seed clams as well. Divers have also recovered the dead shells of juvenile geoducks with holes bored through the umbone, indicative of predation by moon snails (*Polinices lewisii*) and another gastropod, *Natica* sp. (Goodwin and Pease 1989).

Based on the poor survival of unprotected subtidal outplants, WDFW investigated consumption rates by various species suspected of preying on buried geoduck seed: the sea star *Pisaster brevispinus* (167-187 mm radius), the moon snail *P. lewisii* (77-87 mm diameter), red rock crabs (109-142 mm CW), graceful crabs (80-84 mm CW), and rock sole (230-295 mm length). Hatchery seed was separated into four groups of different shell lengths (4 mm, 8 mm, 12 mm, and 16 mm) to examine whether predators exhibited a preference for certain size classes. Clams (110 individuals) were added to experimental and control (no predator) units conditioned with 30 cm of sand. After 4 hours, any geoducks that were not digging were replaced. After 24 hours, three predators of a single species were added to experimental units (equivalent to 2.3 predators/m^2) and allowed to forage for 48 hours. Beattie and Blake (1999) found that each size class of seed was preyed on by every predator species, but did not indicate whether results of size-selective predation were statistically significant. Crabs exhibited the highest consumption rates (Fig. 2). Graceful crabs consumed approximately 30-35% of clams in each size class, whereas red rock crabs consumed proportionately more of the 12 mm and 16 mm clams (ca. 30-50%) than the 4 mm and 8 mm clams (ca. 10-20%). Rock sole consumed proportionally more of the 4 mm size class (ca. 33%) compared to other size classes (ca. 15-20%).

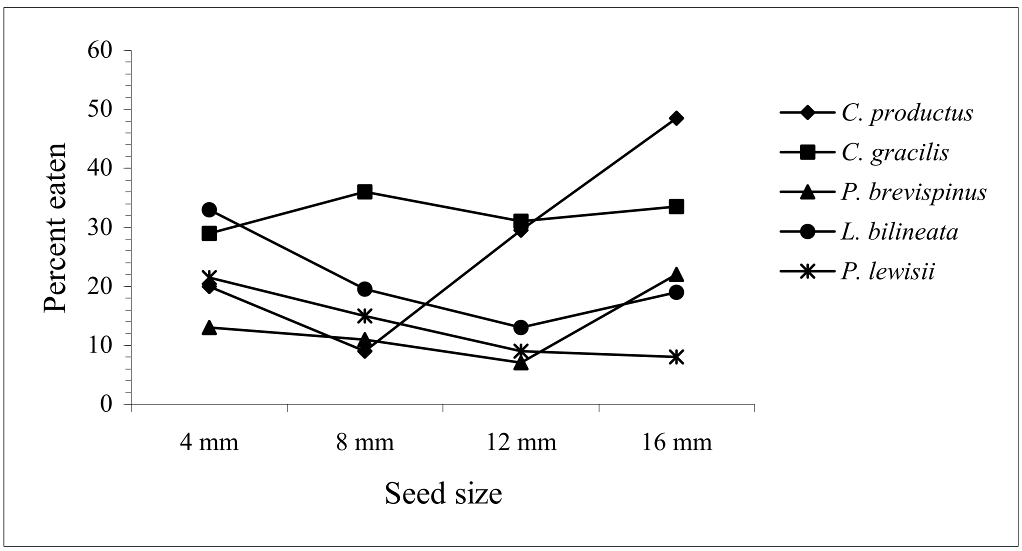


Figure 2. Predation on four size classes of geoduck (*Panopea abrupta*) seed by *Cancer productus*, *Cancer gracilis*, *Pisaster brevispinus*, *Lepidopsetta bilineata*, and *Polinices lewisii* (figure modified from Beattie and Blake 1999).

After laboratory results confirmed buried geoducks were susceptible to predation, WDFW designed and experimentally tested various predator exclusion techniques to increase seed survival in intertidal and subtidal regions. While protective netting has proven successful in manila clam aquaculture (Toba et al. 1992) and improved survival of geoduck seed in experimental trials in which the netting remained intact (Beattie and Blake (1999) citing Dr. Randy Shuman's research from 1987-88 and WDFW research from August 1990 to March 1991), intertidal protective measures have focused primarily on the use of polyvinylchloride (PVC) tubes inserted vertically into the sediment to culture geoduck seed that have been planted manually. Mesh-covered tubes typically are removed within a year of planting after geoducks have achieved a partial depth refuge.

Intertidal geoduck planting tubes with predator exclusion netting

In the summer of 1991, WDFW, with the cooperation of the Washington State Parks and Recreation Commission (Parks), test planted geoducks on four Parks' beaches: Fay Bainbridge Park in Central Puget Sound, Kitsap Memorial Park on Hood Canal, Kopachuck Park in South Puget Sound, and Hope Island Park in South Puget Sound. Tubes used were 30 cm long, and 10 cm and 15 cm in diameter. Two hundred tubes were planted randomly with four to seven seed in a 20 m by 10 m array with the long axis parallel to the shoreline, between + 0.31 m and – 0.31 m mean lower low water. Selected tubes were covered with clam netting. Mean geoduck survival from August 1991 to May 1992 among all four beaches was 40% and ranged from 20-70% among the beaches (Beattie and Blake 1999). Beattie and Blake (1999) did not provide summary statistics or other information to indicate whether seed survival exhibited any trends with respect to factors such tube diameter or the presence of protective clam netting.

In 1992, another experimental trial was initiated at two State Parks in South Puget Sound: Tolmie Park and Kopachuck Park (Beattie and Blake 1999). PVC pipes were

30.5 cm long, and 7.6 cm, 10.2 cm, and 15.2 cm in diameter. On each of the two beaches, 600 tubes were planted with 5 seed per tube. Selected tubes were again protected with netting. Beattie and Blake (1999) reported that survival among all treatments at Kopachuck and Tolmie beaches was approximately 15% and 50%, respectively. Again, no data were available with respect to the effects of tube diameter or protective netting on seed survival. Further investigation and analyses of the original data from these experiments would be useful. While geoduck survival to age-one exhibited variability among sites and between years in these early studies, the general technique of planting seed in mesh-covered PVC tubes was deemed successful in reducing predation. WDFW has since incorporated intertidal geoduck culture into their shellfish enhancement program on public beaches, and considerable commercial development of geoduck culture has occurred in Washington State and British Columbia, Canada (Beattie and Blake 1999).

From the 1970s to early 1990s, WDFW also experimented with subtidal predator exclusion techniques. Clam netting was used in initial trials, but seed survival was extremely low (Beattie and Blake 1999). Despite anchoring the netting into the sediment with reinforcement bar, red rock crabs and graceful crabs were found under the netting. *Polinices lewisii* apparently preyed on protected seed as well based on the recovery of several geoduck valves with drill holes. Given the relative success of PVC protective tubes in reducing intertidal predation, WDFW conducted a small-scale experiment in the early 1990s to test the use of biodegradable tree planting cones to reduce predation on geoduck seed planted in subtidal beds. Divers used water jets to insert cones (20.3 cm length by 7.6 cm diameter opening by 3.8 cm diameter opening) wide-end down into sediments ranging from gravel to mud. Fifteen months after planting, venturi sampling revealed that seed survival in cones was 20% in the sand plot and minimal in both gravel and mud plots (Beattie et al. 1995, Beattie and Blake 1999). In Washington State, subtidal geoduck aquaculture has not advanced beyond these initial studies. Subtidal enhancement and farming efforts have occurred in British Columbia, however. The Underwater Harvester’s Association (UHA) has developed a hydraulic machine that plants geoduck seed subtidally, below the sediment surface, eliminating much of the labor involved in manual placement (Beattie and Blake 1999).

3.4 Geoduck predators and factors that affect consumption rates

3.4.1 Introduction

Crabs, sea stars, gastropods, fish, birds, and mammals are among the most common predators in bivalve-dominated communities (Dame 1996) and are discussed in greater detail below. While our focus is specifically on epibenthic predators of geoducks and other bivalves, we note, however, that predatory infauna could potentially consume geoduck seed. Studies on the east coast of the United States have documented predation on adult and juvenile *Mya arenaria* by infaunal organisms, such as the nemertean worm *Cerebratulus lacteus* (Kalin 1984, Rowell and Woo 1990, Bourque et al. 2001) and the annelid *Nereis virens* (Ambrose 1984, Kraeuter 2001 citing Dean 1981). *N. virens* has also been shown to have a negative effect on population densities of the tube-building amphipod *Corophium volutator* (Commito 1982). While the occurrence of infaunal predation on geoducks has not been studied, it is possible that infaunal predators could have a measurable effect on seed density and distribution as demonstrated for other infaunal prey species in soft-sediment environments (see review by Ambrose 1991).

3.4.2 Crabs

Crabs have been shown to play an important role in influencing infaunal bivalve demographics in marine benthic communities (Virnstein 1977). In the Pacific Northwest, two species of cancrid crabs are believed to be major predators of juvenile geoduck clams. Red rock crabs are distributed widely throughout Puget Sound while graceful crabs are particularly abundant in the southern portions of Puget Sound (Palazzi et al. 2001). Red rock crabs and graceful crabs were ranked ninth and thirteenth by Goodwin and Pease (1987) based on pooled data of frequency of occurrence on surveyed geoduck tracts. The Dungeness crab (*Cancer magister*) is also distributed throughout Puget Sound and was ranked twenty-ninth in overall frequency of occurrence (Goodwin and Pease 1987). While pooled data are informative, the relative abundance of crabs is site-specific. Some tracts have a higher relative abundance of Dungeness crabs while other tracts have a higher relative abundance of red rock crab or graceful crab (Bob Sizemore, WDFW, personal communication).

Crab predation on geoduck siphon

Red rock crabs and graceful crabs have been observed to prey on unprotected clams planted subtidally (WDFW, unpublished data). Divers noted that seed used in planting trials in the 1980s were often chipped or cracked, and suffered high initial mortalities due to predation by crabs, flatfish, and the gastropod *Nassarius* sp. Hatchery-reared geoduck seed, particularly those with thin shells, are vulnerable to breakage as they are harvested from sediment-filled rearing tanks prior to being outplanted. Velasquez (1992a) found that thin-shelled seed were more prevalent in nurseries with relatively high water temperatures and excessive organic material. Shell fragility has important implications for burrowing behavior and seed survival (Velasquez 1992a, 1993). In laboratory experiments, seed clams (14-16 mm SL) were either broken with a light blow from a blunt rod or left intact and added to tanks conditioned with 30 cm of sand. Burrowing activity and success (complete burial) were monitored over a two-day period. Any broken clams that had suffered internal damage were replaced. After two days, three red rock crab predators (103-127 mm CW) were introduced into each tank and allowed to forage for 62 hours. Results revealed that broken seed were less likely to initiate burrowing activity than intact seed, less likely to ultimately bury successfully than intact seed, and suffered greater mortality by crab predators than intact seed due to their inability to achieve a partial depth refuge (Fig. 3) (Velasquez 1993).

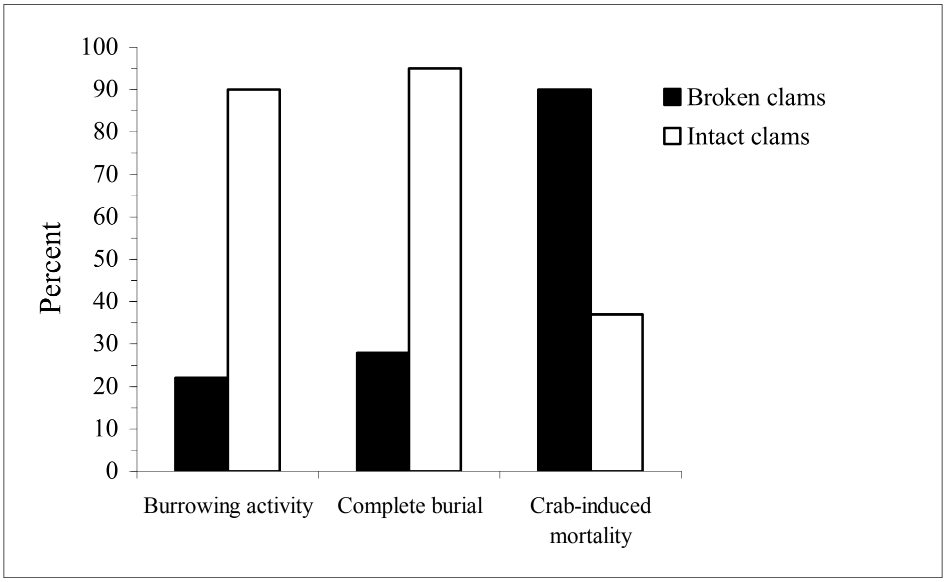


Figure 3. Percent of broken and intact geoduck (*Panopea abrupta*) seed exhibiting burrowing activity two hours after planting, complete burial, and predation-induced mortality. Data from Velasquez (1993).

Dungeness crabs are not identified as a major predator of geoduck seed in published reports. Yet further study of the distribution, length-frequency composition, and foraging behavior of Dungeness crabs on geoduck beds seems warranted, as this species is presumably capable of preying on unprotected geoduck seed. In Grays Harbor, Washington, Stevens et al. (1982) reported that small bivalves (*Cryptomya californica*, *Macoma* sp. and *Tellina* sp.) comprised the major prey category of 0+ (settlement to age 1, $\leq$ 60 mm CW) Dungeness crabs based on stomach content analyses. Ontogenetic (i.e. changing with age) shifts in prey preferences were reported for older crabs: crangonid shrimps (*Crangon* spp.) were the major source of prey for 2+ crabs (61-200 mm CW), while crangonid shrimps and juvenile teleost fishes were the most important prey items for 3+ crabs (101-160 mm CW). Iribarne et al. (1995) reported density-dependent predation by 0+ Dungeness crabs on *Macoma balthica* occurring on mudflat covered with epibenthic shells in Grays Harbor estuary. While recruitment of *M. balthica* was similar in open mud and mud covered with epibenthic shell, bivalve mortality was higher in epibenthic shell habitat compared to open mud due to increased local densities of 0+ crabs within the shell habitat. Palacios (1994) similarly found that 0+ Dungeness crabs preyed on juvenile *Mya arenaria* in laboratory and field experiments and suggested that the distribution and abundance of *M. arenaria* within Grays Harbor was restricted to areas of the estuary where 0+ crabs had limited access, such as high intertidal grounds.

Burial depth, prey size and density, as well as habitat complexity affect crab foraging behavior and consumption rates and have been shown to be important factors in the persistence or extinction of bivalve populations at small (e.g. 0.5 m^2 experimental plots, Seitz et al. 2001) spatial scales. As discussed previously, burial depth is an important refuge for sedentary bivalves. Zaklan and Ydenberg (1997) found that *Cancer productus* excavated significantly fewer *Mya arenaria* buried at 15 cm depth compared to 5 cm depth. In laboratory experiments, Smith et al. (1999) determined that *C. productus* had to spend a significantly greater proportion of total handling time excavating *M. arenaria* that were buried more deeply. When handling time was partitioned into excavation, breakage, and consumption, prey excavation accounted for 23% of total handling time for clams buried at 5 cm depth, 62% at 10 cm depth, and 73% at 15 cm depth. Consequently, both predation rate and prey profitability (energy intake per unit handling time) decreased with depth.

Optimal foraging theory predicts that predators will select prey that maximize their energy return per unit foraging time (Elner and Hughes 1978). Yet decapod crustaceans often consume smaller prey than expected (Lawton and Hughes 1985) to minimize handling time (Palacios 1994) or risk of injury (Juanes 1992). Palacios (1994) found that juvenile Dungeness crabs selectively foraged on smaller size classes of juvenile *Mya arenaria*, to minimize handling time. Creswell and McLay (1990) similarly determined that handling times of *Cancer novaezelandiae* increased with prey size and that crabs selected sizes that minimized time spent foraging. Larger prey could not be crushed; instead, *C. novaezelandiae* had to slowly chip away at shells, which increased handling times (Creswell and Marsden 1990).

Bivalve prey may also find refuge from predation at low prey densities. Results of laboratory and field experiments on the functional responses (prey consumption per predator as a function of prey density) of the blue crab *Callinectes sapidus* on infaunal bivalves *Mya arenaria* and *Macoma balthica* indicate that clam persistence is species- and habitat-specific (Lipcius and Hines 1986, Eggleston et al. 1992, Seitz et al. 2001). Blue crabs have been shown to exhibit a density-dependent functional response to *M.*

balthica in both sand and mud substrates, which enables clams to persist at low densities in the field. Blue crabs also exhibited a density-dependent response to *M. arenaria* in sandy substrates. In muddy sediments, however, the predator exhibited an inversely density-dependent functional response in which the risk of predation to *M. arenaria* actually increased at low prey densities. Bivalves may find refuge at low densities even at high predator densities due to mutual interference between predators (Mansour and Lipcius 1991, Clark et al. 1999).

Habitat structure and complexity also provides refuge for prey populations by reducing crab foraging efficiency. Numerous studies have documented the refuge value of above-ground features of seagrass beds (Heck and Thoman 1981, Summerson and Peterson 1984, Leber 1985, Irlandi and Peterson 1991) as well as below-ground structural features (Virnstein 1977, Summerson and Peterson 1984, Capehart and Hackney 1989) on the densities and distributions of macrofauna. While Irlandi (1997) reported that predation on *Mercenaria mercenaria* was reduced by the presence of seagrass, the degree of refuge varied with patch size, with larger meadows providing greater refuge than small patches. Other emergent structures may serve as prey refuge including epibenthic shell (Arnold 1984, Dumbauld et al. 1993, Skilleter 1994), cobble and rocks (Barshaw and Lavalli 1988), and woody debris (Everett and Ruiz 1993). Skilleter (1994) found, for example, that empty shells of *Rangia cuneata* reduced predation by *Callinectes sapidus* on *Macoma balthica* and *Mya arenaria*. Blue crab predation on *M. mercenaria* has also been shown to be lower in shell and gravel sediments than in sand or mud (Sponaugle and Lawton 1990). While habitat heterogeneity often provides prey with refuge from epibenthic predation, it can have the opposite effect. Survival of bivalves may be reduced in complex habitats (Beal 2000) by preventing clams from reaching their full burial depth (Skilleter 1994) or by concentrating predators that rely on the habitat for their own survival (Wilson et al. 1987, Iribarne et al. 1995). With respect to geoduck clams, Goodwin and Pease (1991) found that *Panopea abrupta* cannot bury as deeply in gravel or shell substrates, possibly rendering them more vulnerable to predators since they would be unable to bury to their full potential.

3.4.3 Sea stars

Many species of sea stars are capable of consuming infaunal clams (Mauzey et al. 1968, Doering 1982) and, where abundant, have been shown to influence soft-sediment community structure (Menge 1982) and reduce population densities of bivalves (Ross et al. 2002). In the Pacific Northwest, the sea stars *Pisaster brevispinus* and *Pycnopodia helianthoides* have been reported to prey on both juvenile and adult *Panopea abrupta* (Sloan and Robinson 1983, Goodwin and Pease 1989, Beattie and Blake 1999).

Pisaster brevispinus is a large, slow-moving species typically associated with soft-bottom habitats. The ability of *P. brevispinus* to extend its circum-oral tube feet down siphon holes makes it particularly adept at extracting large, deeply buried bivalves (van Veldhuizen and Phillips 1978). Mean density of *P. brevispinus* on a subtidal sandbed in British Columbia was 0.018 sea stars/m^2 (mean length, 22.27 cm radius) in a study by Sloan and Robinson (1983). They reported that *P. brevispinus* preyed preferentially on *Panopea abrupta* and the jackknife clam *Solen sicarius* compared to shallow-dwelling species such as *Clinocardium nuttallii* and *Saxidomus giganteus*. *P. abrupta*, which comprised one-third of the sea star's diet, was typically extracted from its burrow and consumed on the sediment surface rather than digested *in situ*. Feeding pits averaged 11.6 cm depth (range 5-18 cm, n = 18) and circum-oral tube feet extended down an average of 16.6 cm (range 12-23 cm, n = 19). These data suggest that *P. brevispinus* can prey on juvenile geoducks buried up to 40 cm depth. Adult clams that are unable to burrow beyond an impenetrable clay or gravel layer are vulnerable as well. Geoduck shells recovered by Sloan and Robinson (1983) after sea star feeding events were those of adult clams (110.0 mm SL ± 29.6 SD) that apparently had been unable to penetrate through a matrix of dense sand, shell, and cobble at 25 cm depth. Beattie and Blake (1999) found that *P. brevispinus* (167-187 mm radius) also preyed on geoduck seed in laboratory experiments (Fig. 2). It consumed proportionally more juveniles in the 16 mm size class (ca. 23%) and proportionally fewer juveniles in the smaller (4 mm, 8 mm, and 12 mm) size classes (ca. 7-14%). Results of studies examining predator-prey size relationships indicate that sea stars select prey relative to predator size, with larger individuals preying preferentially on larger bivalve prey (Paine 1976, Anger et al. 1977, McClintock and Robnett 1986).

The sunflower sea star, *Pycnopodia helianthoides*, is an active, large, multi-armed species whose generalized diet reflects the range of habitats it occupies (Mauzey et al. 1968). Sloan and Robinson (1983) reported a mean density of 0.017 *P. helianthoides*/m^2 (mean length, 17.9 cm radius) at their subtidal study sites and found that *P. helianthoides* preyed principally on *Panopea abrupta* and *Clinocardium nuttallii*. *P. helianthoides* created feeding pits ranging in depth from 6-14 cm (n = 6) and tended to center itself over the edge with half its arms extending into the pit. *P. helianthoides* was capable of excavating deep-burrowing geoducks based on the recovery of large shells (95.8 mm SL ± 3.3 SD) following feeding events, with *P. abrupta* accounting for one-third of its diet. However, Sloan and Robinson (1983) suggested that, in some instances, large geoducks that *P. helianthoides* were consuming had been stolen from *Pisaster brevispinus* that were nearby. *P. helianthoides* is an opportunistic predator and has been observed to approach and remove prey from *P. brevispinus* in other studies (Wobber 1975).

3.4.4 Gastropods

As described previously, the lean basket-whelk *Nassarius mendicus* has been observed feeding on outplanted geoduck seed following broadcast applications to subtidal substrates (Goodwin and Pease 1989). Divers noted that most of the seed attacked by *N. mendicus* were either stressed or injured (WDFW, unpublished data). *N. mendicus* is unlikely to prey on healthy juvenile geoducks buried in the sediment. Britton and Morton (1994) described this species as a microphagous scavenger of fish and bivalve carrion, rather than a predator on infaunal bivalves. *Polinices lewisii* and *Natica* sp. are predators of *Panopea abrupta* based on the recovery of drilled shells during dive surveys (Goodwin and Pease 1989, Beattie and Blake 1999). In laboratory experiments, Beattie and Blake (1999) found that *P. lewisii* (77-87 mm diameter) consumed approximately 21% of 4 mm geoduck seed clams and 15% of 8 mm clams compared to approximately 10% of 12 mm clams and 8% of 16 mm clams (Fig. 2).

Naticid predation has been reported on other infaunal bivalve species as well. Commito (1983) found that *Lunatia heros* preyed on *Mya arenaria* clams less than 30 mm SL. Clams greater than 30 mm SL were thought to have reached either a size or depth refuge from snail predation. *Polinices lewisii* has been observed feeding on the horse clam *Tresus capax* (Wendell et al. 1976) and on the Manila clam *Tapes philippinarum* (Chew 1989, Rogers and Rogers 1989). Chew (1989) found that small moon snails (5-6 mm diameter) preyed on Manila clams as small as 3 mm SL, while larger snails (25-100 mm) fed on larger Manila clams. Rogers and Rogers (1989) also examined size-selective predation by *P. lewisii* on *T. philippinarum*. Results from their intertidal caging experiment revealed that snails were only capable of consuming clams with lengths smaller than the diameter of the snail and that, on average, *P. lewisii* consumed 0.14 clams/snail/day.

3.4.5 Fish

Several species of fish have been observed feeding on geoduck seed including starry flounder (*Platichthys stellatus*), English sole (*Parophrys vetulus*), rock sole (*Lepidopsetta bilineata*), sand sole (*Psettichthys melanostictus*) and pile perch (*Rhacochilus vacca*) (Goodwin and Pease 1989, Beattie and Blake 1999). Divers have noted during surveys that flatfish consume seed ranging in size from 2.4–13 mm SL (WDFW, unpublished data). Other studies have reported finding whole bivalves in the stomachs of epibenthic fish predators such as *P. vetulus* (Williams 1994) and staghorn sculpin, *Leptocottus armatus* (Armstrong 1991). Moller and Rosenberg (1983) found that *Pleuronectes flesus* foraged on *Mya arenaria* up to 12 mm SL. Similarly, Toba et al. (1992) found that *L. bilineata*, *P. vetulus*, and *P. stellatus*, were capable of consuming entire Manila clams (< 20 mm SL).

Epibenthic predators can also exert non-lethal predation pressure on bivalve populations. Studies have shown that siphon-cropping is prevalent among benthic-feeding fishes and crustaceans (Peterson and Quammen 1982, Armstrong 1991, Kamermans and Huitema 1994, Williams 1994; Armstrong et al. 1995). During the course of feeding, infaunal bivalves extend their siphons near or above the sediment-water interface, increasing their exposure to epibenthic predators that may consume these soft tissues. Siphons of *Panopea abrupta* have been found in the stomachs of spiny dogfish (*Squalus acanthia*) and cabezon (*Scorpaenichthys marmoratus*) (Andersen 1971), and divers from WDFW have noted cropped geoduck siphons during surveys of subtidal populations (Goodwin and Pease 1989). Goodwin and Pease (1989) also reported that fishermen have found geoduck siphons in the stomachs of halibut (*Hippoglossus stenolepis*). Siphon-cropping is more frequent in the spring and summer than in the winter when geoducks are less active and spend considerable time with their siphons retracted (Goodwin 1977).

Siphon-cropping has been shown to have negative sublethal effects on bivalve growth. Peterson and Quammen (1982) found that growth of *Protothaca staminea* was significantly lower inside cage controls and uncaged controls than in cages that excluded large predators and croppers. Based on the presence of siphon tips in epibenthic feeding fishes caught over experimental sites and laboratory observations indicating that bivalve feeding activity was unaffected by the presence of croppers, Peterson and Quammen (1982) concluded that lower growth rates of exposed clams resulted from energy being diverted to tissue regeneration. Other studies, however, have shown that the presence of predators can alter the feeding behavior of bivalves: clams may spend less time feeding in the presence of predators or may feed at times when predators are less abundant (Irlandi and Peterson 1991, Nakaoka 2000). Levinton (1971) found that *Macoma tenta*, a deposit-feeding bivalve, feeds only at night, most likely to avoid siphon predation by bottom-feeding fishes. In another study, Kamermans and Huitema (1994) suggested that reduced growth in *Macoma balthica* subjected to browsing by the shrimp *Crangon crangon*, likely resulted from the combination of extra energy required for siphon regeneration, reduced feeding time due to predator avoidance, and a smaller surface area for foraging.

While siphon-cropping may not result in the immediate death of a bivalve, it can affect burial depth, which may, in turn, facilitate secondary predation (Zwarts and Wanink 1989). De Goeij et al. (2001) found that tissue loss increased and burial depth decreased in experimental treatments in which *M. balthica* was exposed to siphon cropping by plaice (*Pleuronectes platessa*) compared to controls in which plaice were absent. *M. balthica*, a facultative deposit/suspension feeding tellinid, extends its siphon out of the sediment to probe for benthic microalgae when deposit feeding. Food intake and growth have been shown to increase with decreasing burying depth (Zaklan and Ydenberg 1997, de Goeij and Luttikhuizen 1998), but so has the risk of predation (Myers et al. 1980). As siphon-cropped clams attempt to regain body condition by burying less deeply, the authors found that whole clams became increasingly vulnerable to probing avian predators, such as oystercatchers and red knots. Although there are some reports of siphon-cropping on geoducks (Andersen 1971, Goodwin and Pease 1989), no published information is available to indicate the extent of cropping on juvenile clams and whether juveniles can or do adjust their burial depth to feed closer to the sediment surface if siphon tissue is lost.

3.4.6 Birds

Waterfowl could be potentially important predators of juvenile *Panopea abrupta* in intertidal and shallow subtidal soft-sediments. No studies have experimentally examined predation on geoduck clams by species of diving ducks, but black scoters (*Melanitta nigra americana*) were suspected of causing significant seed mortality following the removal of predator exclusion tubes at a grow-out site in Thorndyke Bay, Hood Canal (Jonathon Davis, Baywater Inc., personal communication). Scoters were in the immediate area during the entire three-week period in which the mortality occurred, and the ragged, torn siphons of moribund one-year old geoducks were more consistent with waterfowl predation than siphon-cropping by epibenthic fishes.

Studies have documented scoter predation on other local bivalve species. Toba et al. (1992) found that black scoters (*Melanitta nigra americana*), white-winged scoters (*Melanitta fusca delgandi*), and surf scoters (*Melanitta perspicillata*), preyed on Manila clams in Puget Sound, Washington, and that these species accounted for more predation-induced mortality than seagulls or crows. Glude (1964) also found that black scoters, white-winged scoters, and surf scoters consumed Manila clams in Dabob Bay, Washington. Scoters fed primarily on small Manila clams (6-19 mm SL), but were observed feeding on clams up to 25 mm SL. Unlike geoducks, Manila clams are distributed close to the sediment surface. Thompson (1995) suggested, however, that they could attain a partial refuge from predation in coarse substrates. Densities of Manila clams (> 20 mm SL) were greater in experimental plots covered with gravel or gravel and shell than in control plots where scoters could forage more easily.

Waterfowl are key bivalve predators in other soft-sediment communities as well. Yocom and Keller (1961) examined the feeding habits of waterfowl in Humboldt Bay, California, and found that bivalves were second in importance after vegetation. Bivalves were found in the gut contents of mallards (*Anas platyrhynchos*), canvasbacks (*Aythya valisineria*), lesser scaup (*Aythya affinis*), greater scaups (*Aythya marila*), buffelheads (*Bucephala albeola*), and white-winged scoters (*Melanitta deglandi*). Foraging patterns of common eiders (*Somateria molissima dresseri*) in the St. Lawrence estuary revealed that, while eiders preyed preferentially on snails (*Littorina* spp.), *Mya arenaria* accounted for 8% of its diet (Cantin et al. 1974). In Chesapeake Bay, Perry and Uhler (1988) reported that the canvasback *A. valisineria* fed primarily on *Macoma balthica*, but on *M. arenaria*, *Macoma mitchelli*, *Congeria leucophaeta*, and *Rangia cuneata* as well.

3.4.7 Mammals

Along the Pacific coast of the United States, studies have documented predation by sea otters (*Enhydra lutris*) on numerous species of infaunal bivalves (Stephenson 1977, Calkins 1978, Hines and Loughlin 1980). Kvitek et al. (1992) found that sea otters preferred to forage in the shallow waters around the Kodiak Archipelago for the shallow-dwelling Butter clam *Saxidomus giganteus*, and then switched to deeper waters for *Macoma* spp. after the former species became less abundant. Although infaunal biomass was dominated by deep-burrowing clams *Panopea abrupta* and *Tresus capax* at many sites in southeast Alaska, Kvitek and Oliver (1992) found few otter-cracked shells, suggesting that adult clams of these species were able to attain a partial refuge from sea otter predation. Nevertheless, *E. lutris* is capable of excavating clams to a depth of 0.5 m (Hines and Loughlin 1980) and has been shown to successfully prey on deep-burrowing species unable to penetrate through a layer of clay (Kvitek et al. 1988). Shallow-buried juvenile geoducks would be available to sea otters as well, but no studies have specifically examined predation on this age class. Other than sea otters, the only other mammal reported to prey on infaunal bivalves is the raccoon, *Procyon lotor*, which has been observed feeding on intertidal populations of *Mya arenaria* on the east coast of the United States (Kraeuter 2001 citing Gosnor 1979).

4. COMMUNITY AND ECOSYSTEM EFFECTS OF GEODUCKS (UW, Jennifer Ruesink)

4.1 Introduction

Geoducks (*Panopea abrupta*) are large clams that can comprise a substantial portion of infaunal biomass in soft sediments within their range. Little is known of the community- or ecosystem-level effects of geoducks. In this section we provide a general framework for thinking about geoduck interactions, assess available data, and summarize results from other infaunal bivalves that may apply to geoducks. Geoducks potentially influence their environment through four linkages: They may alter water properties through suspension feeding; they may alter sediment properties through deposition of pseudofeces and feces; they may alter the physical attributes of their environment (e.g., sediment grain size or stability), and other species may change distribution accordingly (so-called "ecosystem engineering"); and they may provide a prey resource for consumers, influencing consumer dynamics through "bottom-up" processes related to resource supply. These linkages are summarized in figure 4.

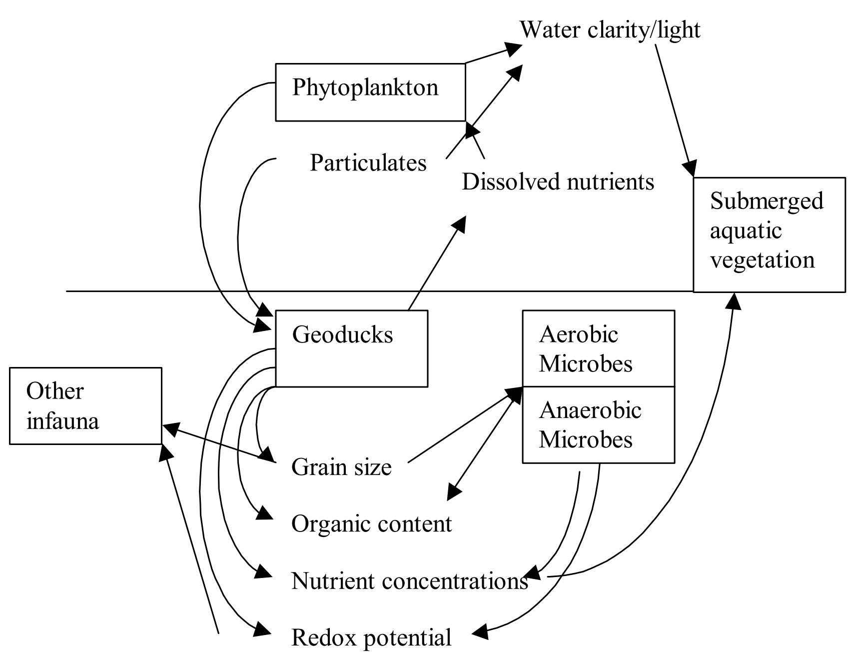


Figure 4. Schematic diagram of community and ecosystem interactions of geoducks.

4.2 Effects on water properties

Geoducks selectively remove phytoplankton during suspension feeding, and gut contents consist of flagellates and diatoms (Goodwin and Pease 1989). Recently-settled geoducks also feed on surface sediments via pedal feeding (King 1985 in Goodwin and Pease 1989). Filtration rates have not been measured explicitly for *P. abrupta* but can be estimated because filtration correlates well with size. If geoducks filter like other bivalves of similar size (150-180 mm, Breen and Shields 1983, Hoffmann et al. 2000), filtration rates range from 7-20 L/hr (Powell et al. 1992). This range represents the difference between so-called "low gear" and "high gear" feeding rates, and lower estimates appear to be more consistent with field observations. Under no-flow conditions, geoducks at densities of $2/m^2$ (Goodwin and Pease 1987) in 6 m of water could filter the water column entirely in 6-18 days.

This simple numerical example leaves some uncertainty about the impacts of geoducks on water properties: flow, water depth, the size of the geoduck bed, and the growth rate of phytoplankton will all modify the effects of filtration. However, clear evidence exists in other systems that bivalves can locally depress phytoplankton abundance. In tidal creeks in North Carolina, water downstream of oyster reefs contained on average 25% less chlorophyll than upstream (Cressman et al. 2003). Chesapeake Bay represents a dramatic large-scale example. There, the loss of historical oyster reefs is implicated in phytoplankton blooms, reduced water clarity, and loss of submerged aquatic vegetation (Moore et al. 1996, Moore and Wetzel 2000, Jackson et al. 2001). Oysters played the central role of transforming pelagic into benthic production. That role has been lost in many east coast estuaries, but in some areas has been replaced by introduced filter feeders. The arrival of *Corbicula fluminea* in the Potomac River estuary improved water clarity and allowed eelgrass to reappear in areas from which it had been absent for 50 years (Phelps 1994). Similarly, *Potamocorbula amurensis* in San Francisco Bay may be reducing phytoplankton and zooplankton densities (Kimmerer et al. 1994, Jassby et al. 2002).

4.3 Effects on sediment properties

Geoducks produce conspicuous feces that remain in the sediment, but sediment properties with and without geoducks have not been measured. In other species, however, benthic-pelagic coupling occurs: water column particulates are removed and deposited on the substrate. Pseudofeces and feces produced by bivalves can increase both sediment organic content and nutrient levels in sediment porewater (Reusch and Williams 1998, Peterson and Heck 2001a). In Florida seagrass beds (*Thallasia testudinum*), the presence of mussels (*Modiolus americanus*) within the beds has been shown to enhance eelgrass productivity (blade growth rate; Peterson and Heck 2001a, b). The mechanistic explanation has been clearly demonstrated: mussels enhance porewater nutrients, which enhance nitrogen and phosphorus content of seagrass blades and lead to faster growth. A similar study has been carried out in southern California examining interactions between eelgrass (*Zostera marina*) and an introduced mussel (*Musculista senhousia*) over a range of densities of each (Reusch and Williams 1998). Mussels were placed in eelgrass beds and near eelgrass transplants at several densities. The study demonstrated that, at high densities, mussels inhibited rhizome extension of eelgrass, but across a range of densities, blade growth rates were enhanced. In contrast, Pennifold and Davis (2001) found that the presence of macrofauna in sediments did not alter nutrient content, but rather influenced nutrient fluxes.

4.4 Effects on community structure

Ecosystem engineers are species that transform habitat in such ways that many other species are affected. Clams have been suggested to play a role as ecosystem engineers in soft sediments (Peterson 1984). Again, however, few data are available for geoducks in particular.

Many species co-occur with geoducks in subtidal and intertidal areas of Puget Sound, including crabs (*Cancer magister*, *C. productus*, *C. gracilis*), sea stars (*Pycnopodia helianthoides*, *Pisaster brevispinus*), flatfish (Family Pleuronectidae), sea pens (*Ptilosarcus gurneyi*), sea cucumber (*Parastichopus californicus*), sea whips (Family Virgulariidae), anemones (*Metridium senile*, *Pachycerianthus fimbriatus*), polychaetes (*Spiochaetopterus* spp. and *Phyllochaetopterus* spp. have tubes that are visible at the surface), other clams (*Tresus* spp., *Saxidomas*, *Clinocardium*), macroalgae (*Laminaria* spp.), hydroids, bryozoa, and small gastropods (Bradbury 1999). Goodwin and Pease (1987) list 40 taxonomic groups commonly associated with geoducks. Six taxa were positively associated with geoducks (based on non-parametric tests, not adjusted for multiple comparisons), including chaetopterid polychaetes, which may provide a settling cue for geoduck larvae. Two taxa were negatively associated: small and large red algae (Goodwin and Pease 1987).

In one analysis in Puget Sound, occurrence of several large benthic species did not differ before (with geoducks) versus after (reduced geoducks) fishing (Bradbury 1999). However, it would be unwise to draw statistical conclusions from this study because the experimental design is prone to type II errors (the probability of finding no effect when in fact differences exist). It would be beneficial to repeat this study with an experimental design that included control sites and quantitative survey data (rather than presence/absence data).

5. SPATIAL STRUCTURE OF GEODUCKS AND OTHER BIVALVE SPECIES (UW, Brent Vadopalas)

5.1 Introduction

Geoducks share many spatial distribution characteristics with other bivalves. Many bivalves aggregate in clusters (Fegley 2001), and exhibit temporal changes in abundance. On broad spatial scales in the inland marine waters of Washington, geoducks are found in all basins and straits. Their spatial distribution is highly variable on smaller scales, however. A review of what is known about their spatial structure reveals the associated vagaries. Relatively little work has been done on geoducks in particular, so information on clams in general is interleafed where necessary.

5.2 Population Density

Goodwin and Pease (1991) performed an in-depth analysis of geoduck density relative to geographic area, latitude, water depth, and sediment type in Puget Sound. The average densities were significantly different for geographic areas, with South Sound the highest at 2.0 geoducks/m^2, and North Sound the lowest at 0.2 geoducks/m^2. The investigators determined that geoduck density increases significantly with latitude. Density also increases with depth, at least to 18 m. Samples were divided into three depth categories. There were significant differences, with 1.4, 2.0, and 2.2 geoducks/m^2 in the shallow (< 9.1 m), middle (9.1-13.7 m), and deep (> 13.7 m) categories, respectively. Samples were also divided into four substrate type categories. Again, there were significant differences in densities, with the lowest in mud (1.2 geoducks/m^2) and the highest in mud-sand and sand (2.1 geoducks/m^2).

5.3 Population Size

Intertidal clams in Puget Sound are likewise surveyed on public beaches by WDFW and tribal biologists except that samples of 0.028 cubic meters (one cubic foot) are taken along each transect to obtain population size estimates for Manila clams (*Tapes philippinarum*), native Littleneck clams (*Protothaca staminea*), and Butter clams (*Saxidomus giganteus*). Targeted by recreational non-tribal fishers, and commercial, ceremonial, and subsistence tribal fishers, the recreational harvest is estimated by expanding fly-over counts of harvesters at low tide. The expansion factor is obtained by a combination of ingress and creel survey (catch per unit effort, or CPUE) data. Intertidal areas that receive very little tribal or non-tribal harvest nevertheless exhibit statistically significant temporal changes in abundance (J. Whitney, WDFW, personal communication).

Similar methods are used to determine population sizes in other bivalve species. For example, Russell (1972) used CPUE data in combination with stratified random samples before and after harvest to estimate size of hard clam (*Mercenaria mercenaria*) populations. Using his estimates, the harvestable biomass estimate was very close to actual (Fegley 2001).

Subtidal hardshell clams, other than geoducks, were surveyed by WDFW from 1967-77 using a venturi dredge to sample both randomly and along transects. For the period 1967-1971, Butter clam abundances for the five management regions ranged from 46 to 1,144 g/m^2 in South Sound and Central Sound, respectively, whereas for native Littleneck clams, the range was 0 g/m^2 in the San Juan Islands to 448 g/m^2 in Central Sound (Goodwin 1973).

Biologists from WDFW and a number of Point-No-Point Treaty tribes perform visual dive transect surveys to determine geoduck population sizes on tracts in each geoduck management region (Fig. 5). The transects are conducted perpendicular to shore between the minus 5.5 m and minus 21.5 m depth contours. Counts are based on visual identification of either a geoduck siphon or a siphon depression sighted along a 0.91 m wide band delineated by the transect line. Visual counts are corrected by a seasonal "show" factor, specific to each tract, to account for the portion of geoducks undetected by virtue of their retracted siphons (Goodwin 1977).

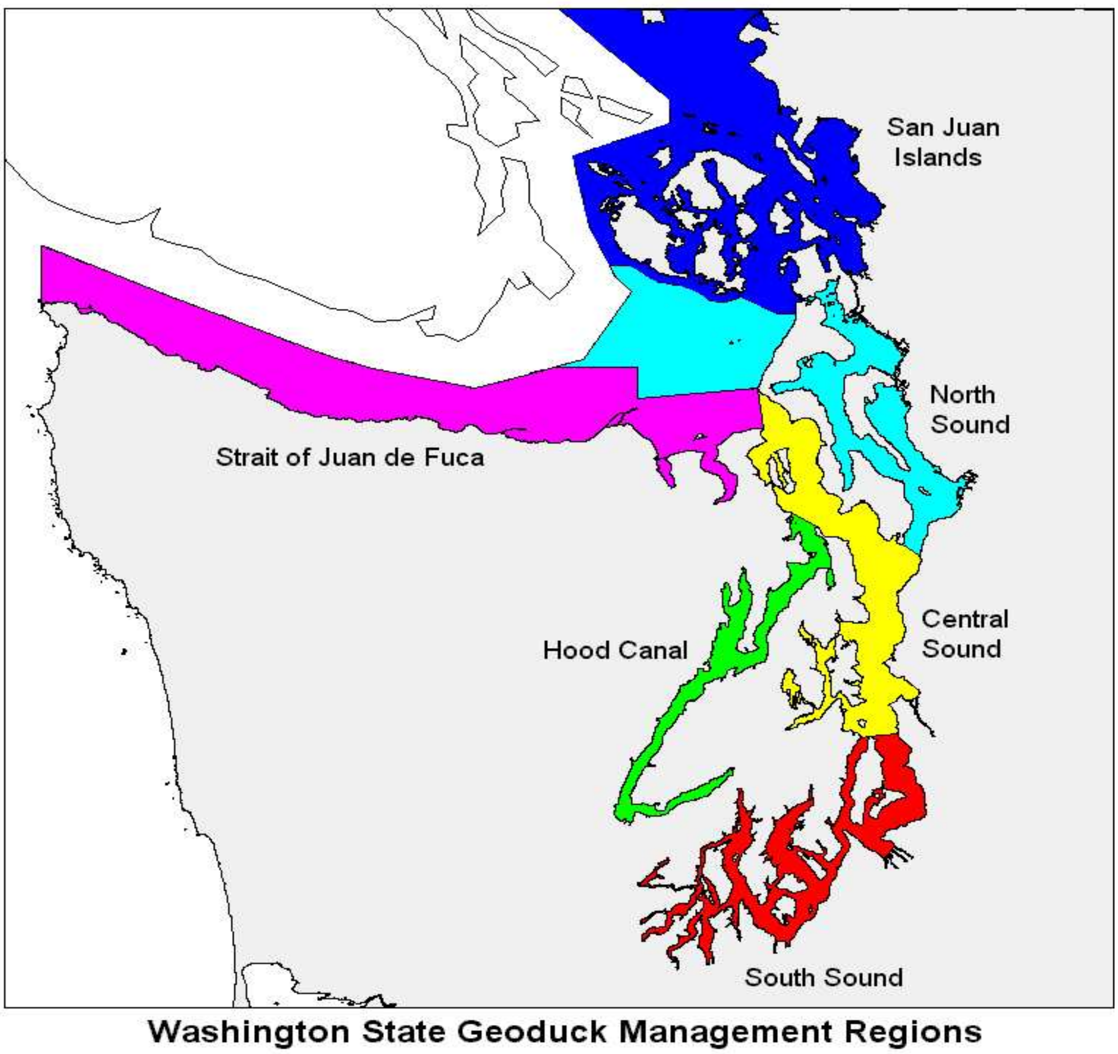


Figure 5. Geoduck management regions in the State of Washington.

From dive survey data, WDFW produces a compilation of known geoduck tracts every year, known as the Geoduck Atlas. In addition to maps showing the approximate location of each tract, the atlas contains information on tract size, geoduck density, and status. Table 1 summarizes some facts from each of the five management regions (Fig. 5).

Table 1. Geoduck (*Panopea abrupta*) tract sizes (hectares, ha) and densities (geoducks/m^2) for five management regions in Puget Sound, Washington. Data compiled from the draft 2003 Geoduck Atlas provided by Bob Sizemore, WDFW.

	Juan de Fuca	**North Sound**	**Central Sound**	**South Sound**	**Hood Canal**
Total area surveyed (ha)	2255	613	3629	3516	2090
largest tract (ha)	484	237	293	187	186
smallest tract (ha)	4	9	2	2	2
average tract (ha)	90	61	66	28	31
highest density (geoducks/m^2)	2	1	3	7	6
Average density (geoducks/m^2)	0.6	0.3	0.9	1.3	1.2

5.4 Aggregation

Many bivalves, especially some clams, tend to be found in aggregations of varying size, rather than randomly distributed (Saila and Gaucher 1966). With broadcast spawners, it seems intuitive that the less dispersed the spawners are, the higher the likelihood of gamete union. Levitan et al. (1992) demonstrated that fertilization success increases dramatically with proximity in the sea urchin. Systematic sampling using quadrats and transects may not be ideal for the characterization of the spatial distribution of clams, but are frequently used for their logistical ease in the field. In a quadrat study on the hard clam, *Mercenaria mercenaria*, 22% of the samples contained high densities and 29% contained very few or no clams (Saila et al. 1967). In this study, the high-density areas were encircled by areas with the second highest density, which were in turn encircled by the third density level. Goodwin and Pease (1991) analyzed 8589 quadrats, each 41.8 m^2, taken throughout Puget Sound. The average number of geoducks per quadrat was 69.3, ranging from 0-940.5 geoducks. Such a wide variance indicates geoducks were not randomly distributed, but were contagiously distributed in clusters or "clumps." These aggregations averaged 109 individuals. Whether the densities of geoducks follow the radiating pattern seen in *Mercenaria mercenaria* is not known. Campbell et al. (1998) characterized the aggregation pattern within a geoduck bed as a Type III concentration (Hilborn and Walters 1992), with most locations exhibiting intermediate density, and fewer locations with either low or high abundance. The aggregating behavior of geoducks has been suggested to result from larval attraction to pheromones, patchy distribution of substrate type, or biotic attractants or deterrents (Goodwin and Pease 1991).

5.5 Temporal Changes

From WDFW intertidal clam population surveys, data suggest that even on beaches with little or no known recreational harvest, intertidal clam population densities change from year to year (J. Whitney, WDFW, personal communication). It has not been determined whether these population size differences are due to cyclical changes in demographics or rather due to biotic or abiotic factors. With geoducks, the best available tools to discern temporal change are the 15 recovery plots currently being monitored by WDFW, and the age frequency histograms that show pre-exploitation levels of year classes. Two recent age frequency histograms from previously unexploited geoduck tracts indicate strong shifts in year class strength, with long periods of little or no recruitment punctuated by massive recruitment. It has been suggested that an important advantage of broadcast spawning and pelagic larvae may be, in addition to the dispersal potential, the periodic high success in recruitment (Ripley 1998). Longevity affords the species the potential for population growth by "gambling" on very large recruitment events (Ripley 1988). Whether this strategy is common in geoducks is unknown.

5.6 Dispersal

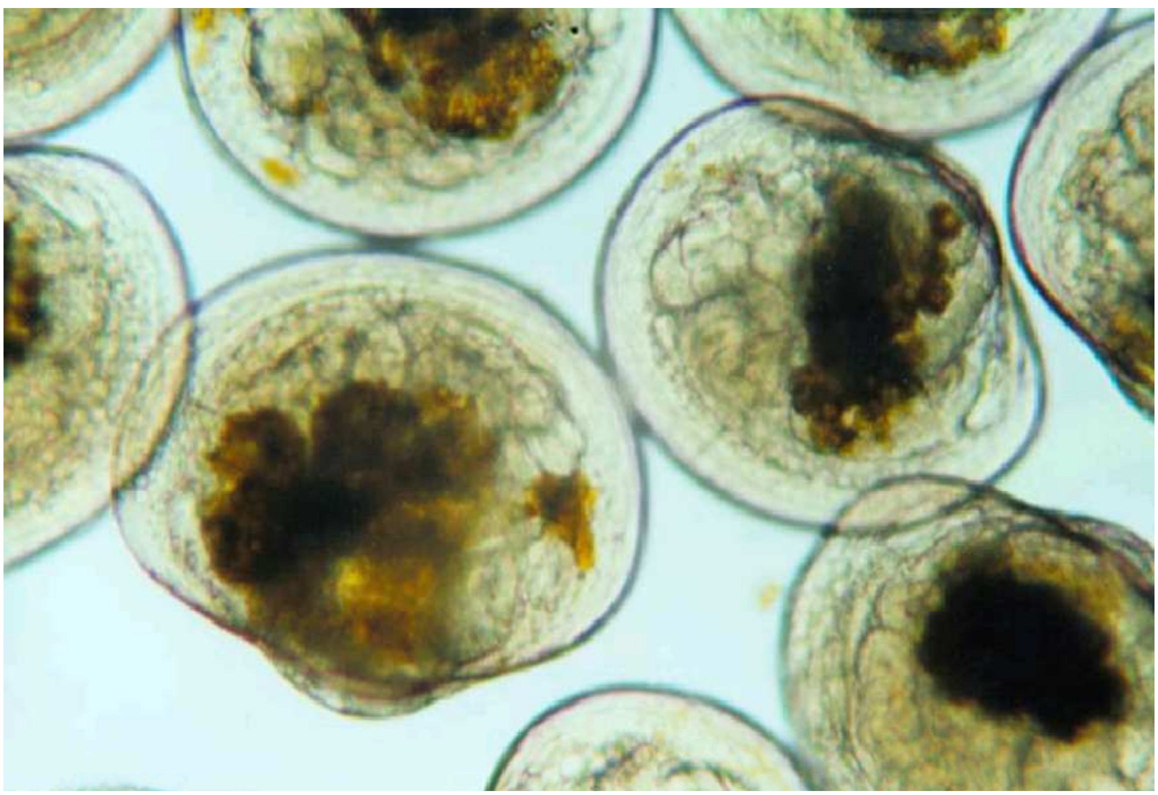
Many clams are capable of some active vertical and lateral movement by virtue of their foot and in response to wave action, tidal movement, or passive movement due to substrate displacement by storms, strong currents, or disturbance (Yonge and Thompson 1976, Prezant et al. 1990). Geoducks, on the other hand, are unable to move as adults. Capable of digging as juveniles to at least 0.3-0.5 m (Campbell et al. 1998), as adults they attain depths of 0.6-1.0 m. The vestigial foot in the adult is disproportionately small relative to the juvenile foot. Adult movement is restricted to siphon extension and retraction. The adult, once exposed, is unable either to right itself or dig into the substrate (Goodwin and Pease 1989).

6. GENETIC-BASED DIFFERENCES AT THE POPULATION LEVEL, IMPLICATIONS FOR GEODUCK STOCKS, AND RISK REDUCTION (UW, Brent Vadopalas)

6.1 Population Genetics

The extent of gene flow and effective population size (N_e) determines the potential for neutral genetic differentiation among natural populations. Gene flow is correlated with dispersal ability in many organisms (Bohonak 1999), including many marine fishes and species of shellfish (reviewed in Shaklee and Bentzen 1998). In sedentary marine bivalves, dispersal and gene flow occur only during the pelagic larval phase. Gene flow and larval dispersal may be correlated with spatial distribution in marine mollusks (Johnson et al. 2001), and a number of investigators have failed to falsify the null hypothesis of panmixia at broad geographic scales in a variety of broadcast spawning marine species with pelagic larvae (e.g. *Littorina striata* (De Wolf et al. 2000); *Mytilus galloprovincialis* (Skalamera et al. 1999)). Nevertheless, some studies have demonstrated genetic structuring at different geographic scales in a variety of marine invertebrate species with pelagic larvae such as the American oyster, *Crassostrea* *virginica,* (Karl and Avise 1992), the sea urchins *Strongylocentrotus purpuratus* ((Edmands et al. 1996)) and *S. franciscanus* (Moberg and Burton 2000), and the black abalone *Haliotis cracherodii* (Hamm and Burton 2000). On smaller geographic scales, for example, genetic structure was detected in the limpet *Siphonaria jeanae* (Johnson and Black 1984), the oyster *Crassostrea virginica* (King 1986), and cockles *Cerastoderma glaucum* (Mariani et al. 2002).

The complex hydrology and bathymetry of Puget Sound in Washington State suggests the potential for restricted dispersal and population subdivision of marine invertebrates in the region. On the other hand, Puget Sound's freshwater inputs and their typical estuarine surface outflow increase the propensity of passive surface particles to disperse in a seaward direction. Molluscan populations colonized by pelagic larvae drifting seaward from populations in inner inlets could thus exhibit either genetic homogeneity or directional gene flow.



Geoduck larvae

With the oldest recorded geoduck estimated to be 168 years, geoducks are among the longest-lived bivalves known. Random sampling of year classes within each collection minimizes the effect of genetic drift due to overlapping generations (Jorde and Ryman 1995), and buffers against genetic differentiation by boosting effective population size (Francois Balloux, University of Edinburgh, personal communication). Experimental evidence indicates mean fecundities of 40 million eggs per year (Beattie 1992). A species may employ the strategy of high fecundity to overcome the spatial and temporal odds of gamete union (Hedgecock 1994) and/or larval survival, or to maximize dispersal (Johnson et al. 2001). Thus, the high fecundity and longevity of *Panopea abrupta* may maximize genetic homogeneity.

An unpublished study by WDFW (Phelps 1993) examined the genetic variation among three Puget Sound geoduck collections using a suite of 15 allozyme loci. The analyses were hampered by loss of enzyme activity at more than 10 loci in over 50% of one of the samples, so the data are questionable. The report concluded that gene flow is restricted among the three collections from Hood Canal, South Puget Sound, and Port Townsend.

Using the cytochrome oxidase III subunit (COIII) of the mitochondrial genome, Van Koeveringe (1998) investigated the genetic population structure of geoducks in British Columbia, but was unable to falsify the null hypothesis of panmixia. Statistical power to detect subdivisions was low, owing to two primary factors. The first was due to the use of a single locus, and the second to small sample sizes averaging 6.5 individuals with a low of three individuals.

More recently, an additional population genetic study was conducted on British Columbia geoducks funded by the Underwater Harvesters Association. This study used microsatellite DNA and larger sample sizes, so the results may be more robust, but the results of this study have not yet been published.

Investigators from the University of Washington and WDFW (Vadopalas et al. in review) examined population differentiation among collections from sites in the Strait of Juan de Fuca – Georgia Strait – Puget Sound complex using 11 variable allozyme and seven microsatellite loci. Both marker classes were concordant in the detection of genetic differentiation of the Freshwater Bay collection in the Strait of Juan de Fuca from others. There was also concordance in the apparent genetic homogeneity among most other collections. The null hypotheses of temporal and within-sample genetic homogeneity in two large collections of *Panopea abrupta* were also tested.

Highlights of this study are:

- The mean expected heterozygosities for microsatellites (0.94) and allozymes (0.39) were similar to those found in other marine bivalves.
- Similar patterns of genetic differentiation were detected with microsatellites and allozymes.
- Similar, very low levels of genetic differentiation were found on three spatial scales: the sub-kilometer scale within one geoduck tract, on the scale of Puget Sound, and between Alaska and Washington populations.
- After examining the genetic relationships within and between year classes in two locations, the differentiation does not appear likely to be due to a strong bias in reproductive success, notwithstanding the large variation in year class strength.
- The genetic differentiation detected is not amenable to a simple island or isolation by distance model; the many factors at play in this complex estuarine environment make it difficult to rule out more cryptic patterns of geographic isolation.

These results are similar to those of Johnson and Black (1984) and Edmands et al. (1996) who found what appeared to be stochastic genetic differentiation in marine invertebrates (*Siphonaria jeanae* and *Strongylocentrotus purpuratus*, respectively), with genetic homogeneity on a broad spatial scale and heterogeneity on a fine scale. Similar observations for other marine taxa exist (see Shaklee and Bentzen 1998 for a review). The asynchrony in recruitment between the two intensively sampled tracts (n >1000), one in South Sound and one in Hood Canal, suggests that the genetic differentiation on both the scale of Puget Sound and within tracts may be driven by such settlement variation.

6.2 Implications concerning wild and "seeded" stocks

For geoducks, what are the genetic risks to wild populations associated with intertidal and/or subtidal aquaculture? Genetic risk is broadly defined as exposing a natural population to genetic change by human action (Currens and Busack 1995). The apparently stochastic genetic differentiation at all spatial scales investigated may simply indicate complex settlement patterns. Disruption of such random genetic patterns via aquaculture activities may be difficult to imagine. Nevertheless, there may be genetic risks if domesticated stocks interbreed with their wild counterparts. These risks center on the potential loss of natural genetic variation in a population, which serves to buffer the population against natural selective forces.

Any genetic change brought about by human control of a hatchery environment can be defined as domestication (Currens and Busack 1995). For example, the selection processes in a shellfish hatchery, *by design*, are vastly different from the selection processes in the natural environment. Like most bivalves under culture, the life history of geoduck includes very high mortalities at the larval stages (type III survivorship). These mortalities can be random with respect to genotype, or there may be selective forces at work. In either case, the hatchery environment is usually designed to minimize larval mortalities (i.e. to relax many selective forces). Active artificial selection may take place through breeding programs, culling of larval stocks, or environmental manipulations in the hatchery. The extremely high fecundity of geoducks, typical of many marine fish and invertebrates, can result in reduced effective population size in the hatchery, because relatively few individuals can contribute large quantities of eggs. This can result in a drastic reduction of genetic variability in the progeny. Once outplanted, purifying selection will not necessarily purge effects of domestication in the same or subsequent generations, because the genes normally under selection during the hatchery period will not necessarily be the same genes subjected to selection during adulthood or subsequent generations.

6.3 Risk Reduction

Broodstock can be collected each year from the wild population with which their progeny will potentially interact. This would avoid both the mixing of stocks, and the perpetuation of genetic changes brought about via hatchery domestication. The use of large numbers of wild broodstock can help insure the retention of natural variability in the offspring, as long as roughly equal reproductive success can be ensured. A hatchery environment can be designed to mimic as closely as possible the natural environment, so that the selection regimes are similar (Maynard et al. 1995).

One of the most risk-averse strategies would include complete physical isolation of the cultured populations. While in some species this is possible primarily through land-based aquaculture, in geoducks current culture methodology relies on intertidal outplants.

The utilization of sex control of cultured populations has been frequently advocated to circumvent genetic change to wild populations (Piferrer and Donaldson 1993). The production of monosex populations for release has the most utility if used in exotics (Thorgaard and Allen 1987, Quillet et al. 1991) unless accompanied by some form of sterility, which provides a form of genetic separation of cultured and wild populations. Sterility can be conferred on shellfish primarily via triploid induction. Triploid bivalves that exhibit reduced or absent gonadogenesis or gametogenesis have been utilized in some cases, produced either by crossing tetraploids and diploids (Guo et al. 1996), or by administering some form of shock to developing zygotes to suppress either the first or second polar body extrusion (see Beaumont and Fairbrother 1991 for a review). Although such techniques have been developed for *Panopea abrupta* (Vadopalas and Davis 2004), in order to be risk-averse, the efficacy of triploidy in conferring sterility, and the permanence of the triploid state must be verified prior to utilization of the technique.

For commercial aquaculture, harvest management of geoducks may have some utility for risk reduction. While geoducks are outplanted for 4-6 years (J.P. Davis, Taylor Resources Inc., personal communication), they are sexually mature and liable to spawn only for their final year or two before harvest. This truncation of the reproductive period reduces the chances of lifetime reproductive success by a factor of about 29 (from geoduck life table data (Bradbury and Tagart 2001) and unpublished age frequency data). Additionally, a highly skewed sex ratio may exist among young geoducks. Andersen (1971) reported 94.4% males among individuals with shell length <100mm, and in another study the proportion of males for individuals <11 years old was 90% (Sloan and Robinson 1984). If such strongly skewed sex ratios remain among commercially grown geoducks until harvest, the likelihood of reproductive success among cultured geoducks would be significantly reduced. This is especially true if the watercourse distance between cultured and wild geoduck aggregations is great enough to ensure adequate gamete cloud dilution and/or low gamete survival, so that downstream fertilizations are avoided.

Proximity and spawning synchrony are the strongest predictors of individual reproductive success. Cultured geoducks are typically planted in much higher densities than occur in the natural environment. If both male and female cultured geoducks spawn, and do so with some degree of synchrony, the likelihood of gamete union increases exponentially with proximity. Densities in wild aggregations in Puget Sound average 1.7 geoducks/m^2 (Goodwin and Pease 1991), while intertidal culture densities average about 13.5 geoducks/m^2 (J.P. Davis, personal communication), greater by a factor of about 8. The likelihood of spawning success would be significantly higher among cultured than among wild geoducks. It is important to note that under this scenario, most of the cultured-wild genetic interactions will occur between their naturalized progeny and wild geoducks, rather than direct interaction between outplants and their wild counterparts. As mentioned above, fertilization success depends on proximity. Gamete age is another factor that affects fertilization success. The age at which gametes become nonviable affects the distance gametes may travel before fertilization and successful zygote formation. Little information is available on geoduck gamete viability, but eggs are viable for at least six hours (Vadopalas and Davis, unpublished data).

Any avoidance of genetic risk via harvest management may be counteracted by the increased probability of individual reproductive success among cultured geoducks and the naturalization of their progeny (notwithstanding potential inbreeding depression and whether and where they settle). Using sterile outplants and/or managing harvest to preempt reproduction could mitigate risks by reducing cultured/wild interactions.

7. DESCRIPTION OF CURRENT COMMERCIAL GEODUCK HATCHERY PRACTICES (Baywater, Inc., Jonathan P. Davis)

7.1 History and current status of private and government sponsored geoduck hatchery operations in the United States

Geoducks have been a part of native fisheries and the object of sport fishers for many years, although commercial harvesting was prohibited by statute in Washington prior to 1969. Following the discovery of large numbers of subtidal geoduck beds, the Washington Department of Fisheries (WDF) sought permission from the Washington State legislature to alter the laws governing commercial fishing for this species. In turn, the WA State legislature created a new fishery to be co-managed by WDF and WDNR. As a result, a geoduck dive fishery was established in 1970 with initial landings of less than 100,000 lbs (WDF 1984). Following the establishment of markets in Japan for processed geoduck in 1974 and increased live exports to China (Hong Kong) beginning in the late 1980s, considerably greater interest in the harvest of wild stocks occurred in both Washington State and British Columbia. Harvest of live geoduck from Washington waters in 1998 had a value of US$13.5 million (WDNR 1998). The 1994 Rafeedie shellfish decision was a seminal moment in Washington State fisheries management as the Federal decision upheld treaty rights of several Native American tribes to harvest shellfish from state waters and as a result allocated 50% of the annual allocation of geoduck to the tribes. As a result, current State/Tribal Geoduck Harvest Plans are formulated annually to allocate the allowable geoduck catch to tribal and non-tribal commercial interests.

Interest in the culture of geoducks coincided with the rapid development of the dive fishery in Washington State, and considerable effort was expended at the WDF State Shellfish hatchery in Brinnon, Washington, to develop methods for the cultivation of geoducks to be used to enhance depleted beds as a result of fishing pressure due to commercial harvest. Research on embryogenesis (Goodwin 1973), larval development (Goodwin et al. 1979), and culture and enhancement efforts (Beattie 1992, Beattie and Goodwin 1993) by the WDF resulted in the establishment of basic methods for the aquaculture production of geoducks that have been adapted by the private aquaculture sector in Washington State, and to a lesser extent British Columbia.

Culture methods employed by the WDFW Pt. Whitney Shellfish Laboratory were adapted from those used for other bivalves, principally oysters and other clams. Adult clams were brought into the hatchery and held in flowing seawater at ambient temperatures (9-12 °C) until needed for spawning. A small increase in seawater temperature and the addition of cultured microalgae to the spawning tank usually stimulated a percentage of animals to spawn. Typically, clams would be collected in October – April, brought into the hatchery and held at 9-10 °C without supplemental food for 2-3 weeks. On the day of spawn attempts, water was warmed to 14-15 °C over a 3-4 hour period and the microalgae *Pavlova lutheri* added to the spawning tank as an additional stimulus (Goodwin et al. 1979). Males would typically spawn first, followed by females. In subsequent years, temperatures inducing spawning were 8.5-16 °C, but more typically were in the range of 12-14 °C. Clams that spawned could be returned to holding tanks and utilized again within 1-2 months. Females would typically produce 7-10 million eggs per spawning event (Goodwin et al. 1979).

The larval period for geoducks reared by WDFW personnel ranged from 16-47 days, again depending on rearing temperature and other factors. Early culture efforts were plagued by low larval survivorship, likely due to bacterial contamination of cultures; however, diligence by WDFW biologists resulted in large numbers of post-larvae being produced. Larval foods used for the production of geoducks at Pt. Whitney included *Phaeodactylum tricornutum*, *P. lutheri*, *Isochrysi galbana* and *Pseudoisochrysis paradoxa* at densities of approximately 50 million cells per L. After 30 days @ 17.6 °C, the size of larvae competent to settle and metamorphose was 377 microns (Goodwin et al. 1979). Later work on larval culture resulted in other microalgae being utilized, including *Chaetoceros calcitrans* and *Thalassiosira pseudonana* (3H) fed to larvae larger than 200 microns in shell length and produced pediveliger larvae after 18 days (Cooper and Pease (unpublished manuscript).

Later innovations at the WDFW shellfish laboratory included the development of large, sand-based nursery systems with extensive utilization of under-substrate piping that enabled the large-scale production of juvenile clams for outplanting in harvested geoduck tracts (Beattie 1992). The purpose of hatchery seed production was to enhance geoduck beds depleted as a result of the commercial dive fishery. Though the production of large quantities of seed was accomplished through the hatchery and land-based nursery systems developed at Pt. Whitney, the survivorship of seed deposited on subtidal geoduck tracts was very low and after many seeding attempts, WDFW abandoned its efforts in geoduck subtidal enhancement in 1991 (Beattie 1992). Following abandonment of sub-tidal plantings, WDFW continued small-scale experiments focused on developing intertidal planting methods utilizing PVC pipe sections, vexar mesh shellfish bags and other enclosures. Results were encouraging with high survivorship and rapid growth occurring in enclosures that precluded predation from crabs and fishes (Beattie, J.H. and J.P. Davis, unpublished data). These efforts were expanded to include intertidal enhancement efforts on various Washington State park tidelands in the 1990s with varying success.

Intertidal geoduck culture using PVC tubes

7.2 Brief history and current status of private and government sponsored geoduck hatchery operations outside of the United States

Due to the high value of wild geoduck on world markets (primarily Japan and China), and emerging interest in farmed production of geoducks, interest in aquaculture production of *Panopea abrupta* has occurred outside of the United States. Efforts in British Columbia (BC) to farm geoduck have met with varying success in the last ten years. Through outreach efforts by WDFW personnel, methods for hatchery cultivation of geoducks were successfully transferred to bivalve hatcheries in BC. At least three BC hatcheries have produced commercial quantities of seed at one time or another over the last five years. The Underwater Harvesters Association (UHA) in conjunction with Island Scallop, a Vancouver Island fish and shellfish hatchery, and FAN Seafoods undertook initial hatchery and seeding efforts in BC. Sections of the Strait of Georgia have been reseeded since 1994 using an underwater planting device with varying success. Production of geoduck seed by Island Scallop has utilized routine hatchery production of pediveligers. The need for large quantities of microalgae for post settlement nursery culture of juveniles to a planting size of at least 10 mm resulted in a shift from land-based nurseries to raft-based floating upwelling systems, or FLUPSY's to take advantage of natural phytoplankton production. FLUPSY production of seed was relatively successful, but quantities were always limiting to the demand for large seed, and subsequent hatchery failures in 2003, internal disruptions in supplies and the need for long grow out periods necessary for subtidally planted geoducks in BC have resulted in some industry retraction. The prospects for seed production in 2003-04 are unclear; two of the major hatcheries in Canada (Island Scallop and Unique Sea farms) may not be producing significant quantities of seed in 2004, although limited production may occur from a joint government /industry venture utilizing space at the DFO Pacific Biological Station in Nanaimo.

Interest in hatchery production of geoducks has extended to Argentina, China and New Zealand. The Argentinean geoduck (*P. abbreviata*) is currently being studied for possible exploitation (see Ciocco 2000). In China there may be some limited geoduck (*P. abrupta* and/or *P. japonica*) culture taking place in Dalian in the northern Yellow Sea, although few details are available as to what may be occurring (J. Gibbons, personal communication). The culture of *Panopea zelandica* has recently been initiated at the Cawthron Institute in Nelson, NZ, with an emphasis on larval and seed development. Information on larval culture indicates that this species may be easier to rear than *P. abrupta* as gametes may be stripped from adults with apparent ease, the larval period is shorter, and pediveligers are competent to settle and metamorphose at a much smaller size (Gribben and Hay 2003). Little farmed product has been harvested to date as the industry is very small. Interest in the harvest of *Panopea globosa* in Mexico is also occurring. This native geoduck occurs in high densities at the head of the Gulf of California on the western side near the mouth of the Colorado river and is currently being harvested, shipped to Los Angeles, and air-freighted to Hong Kong. Product quality is reported to be only fair, and problems exist with respect to shelf life and meat quality (J. Gibbons, personal communication).

7.3 Current status of geoduck larval and nursery culture in Washington State

The past 20 years has seen the emergence of intensive aquaculture directed towards the hatchery rearing of geoduck clams, *Panopea abrupta*. Much of this work was pioneered at the WDF (now WDFW) shellfish laboratory at Pt. Whitney on Hood Canal, Washington, by Lynn Goodwin, Warren Schaul, Ken Cooper, Hal Beattie and Ron Zebal among others in order to generate geoduck juveniles for enhancing geoduck beds that had been harvested. While reseeding efforts by the State of Washington were largely a failure, the technologies developed to rear geoducks were successful and readily adopted by private industry. Since the mid 1990s, private hatchery operations have advanced the science significantly such that the production of juvenile geoduck is now relatively routine. The innovations that have made this possible involve a close adherence to quality control measures as geoduck larvae and small seed are very sensitive to adverse water quality (e.g. physical conditions, pathogens, poor microalgal food quality) and will quickly succumb unless close attention is paid to all aspects of larval, algal, and seed production systems. What follows is not a hatchery manual per se for rearing *P. abrupta*, but rather a supplement for hatchery operators familiar with bivalve culture generally who may wish to rear larvae such as geoduck that are relatively difficult to rear compared to other species.

7.4 Hatchery infrastructure

7.4.1 Seawater source and treatment

A reliable source of electricity, fresh and saltwater, and availability to an educated labor source is extremely critical to successful bivalve culture. In addition, siting the facility in a locale with abundant sunshine to augment algal culture is highly advantageous, as well. The primary determinant of successful marine bivalve hatcheries, however, is proper siting of the facility in a location where incoming seawater is reliably clean, cold, and free of inorganic and organic pollutants on a year-round basis. The worst source of seawater for bivalve production, for example, is that from moderately eutrophic areas with seasonally high algal content and subsequent bacterial loading, which it turns out, is often the case for many locations in Washington State. Often the best source of water for shellfish culture is particle free water obtained via a well drilled at an angle into the ground such that the drill point contacts seawater outside of or below the typical fresh water lens that constitutes the groundwater on the shorefront and upland areas. Seawater from wells is often of high quality and maintains a consistent chemical constitution, salinity, and temperature year round. Salt-water wells may, however, contain high levels of dissolved minerals, particularly iron that will become oxidized on contact with the atmosphere. Removal of dissolved metals is relatively easily accomplished prior to use, as iron oxides will stain tanks and is possibly toxic to bivalve larvae.

Dual intake lines consisting of polyethylene pipe taking water from below the thermocline and regions of high biological activity are excellent sources of seawater, as well. Dual lines are advised because the piping will foul with marine invertebrates over time and a clean-out of the lines will be periodically required such that the hatchery operator will wish to leave one line fallow for a period of weeks, alternating use with the back-up line as needed. Also, the ability to back-flush intake lines is advisable in order to remove fouling materials from the line at the intake side. A simple screen or grate on the intake will preclude fish and larger invertebrates from being entrained. A variable speed centrifugal pump is advised for pumping seawater and delivering it to the hatchery with sufficient pressure to ensure adequate supply. In order to reduce head pressure and pumping costs, it is advisable to install the pump as close to sea level as possible in order to reduce the pull of seawater to the pump head and therefore maximize the push of water uphill through the intake line to the hatchery facility.

Successful marine bivalve larval culture relies extensively on improvements made to the quality of incoming water. Modern hatcheries have a variety of means available to sequentially filter, heat, de-gas, irradiate and “finish” incoming water from ambient sources. Once seawater is pumped into the facility, “treatment” of water is typically accomplished by filtration utilizing sand or cartridge filters to initially filter water to nominally remove particles greater than 30-50 microns in diameter. Sequential secondary cartridge filtration follows with particle removal to 5 and at least 1 micron, respectively. Filtered seawater may also be UV irradiated if bacterial loading of incoming seawater is suspected, and “finished” by passing the filtered, UV treated seawater through activated carbon filters. If either low or high levels of dissolved gasses are suspected to remain in the treated seawater, seawater may be passed though a degassing chamber to bring seawater to saturation for that temperature. Heating of seawater may be accomplished in a variety of ways; typical methods involve titanium plate heat exchangers that transfer heat from either a steam or hot water closed system to incoming seawater. The hatchery infrastructure must have the capability of heating seawater 10 °C at a rate of at least 100 L per minute to enable both larval and algal culture on a routine basis. Heating seawater will require either an oil or natural gas fired boiler to produce hot water or steam, and back up generation equipment is recommended to maintain the oil or gas burners, blowers, heat and lighting for algal cultures, etc., in the event of electrical power loss. The resulting seawater, whether UV irradiated or not, is suitable for geoduck culture at this stage of treatment.

7.4.2 Larval culture equipment

Large volume culture vessels are preferred for geoducks as density dependent interactions will frequently compromise larval cultures due to high surface bacterial loading on vessel walls. The WDFW hatchery facility and the larger hatcheries in Washington State (Taylor Resources and Coast Seafoods) routinely utilize 40,000 L fiberglass tanks to rear all commercially important bivalves reared in the Pacific Northwest. Smaller tanks will certainly suffice, however the maintenance of relatively low larval culture density of geoducks precludes the production of large numbers of seed clams in smaller tanks unless the operator wishes to maintain large numbers of culture vessels. Other equipment associated with geoduck culture is that typically used for the rearing of other bivalve larvae. Screens for sieving larvae, setting systems, and algal food production (except as noted below) are similar to that for other bivalves and do not require any extensive modifications.

Hatchery hygiene is of paramount importance for rearing any bivalves as pathogenic bacteria and protozoans are invasive, colonize surfaces very quickly, and will rapidly induce a pathogenic response in most invertebrate larvae. The use of antibiotics for routine production rearing of larvae is strongly discouraged, and is illegal in most circumstances. At a minimum, twice monthly and ideally weekly all surfaces contacting seawater should be sanitized including rearing tanks, hoses, hard PVC plumbing, soft plumbing including hoses, and feed lines and glassware. Screens, filters, pumps, and other equipment used to move seawater, algae, or larvae around the facility should be sanitized after every use. Sanitation procedures will vary with the facility, however the use of either a chlorine based cleaner (e.g. Clorox) or acetic acid based cleaner (e.g. Vortex) is recommended to be used as directed for sanitizing purposes. The acetic acid based sanitizers are particularly attractive as they are routinely used in food production facilities for maintaining sanitized surfaces, are relatively non-toxic when dilute, clean up easily, and are safely disposed of by dilution. Adherence to human health and safety should be closely adhered to regarding the use of respirators and other safety equipment when handling any chemicals, and chlorine based cleaners should always be neutralized with sodium thiosulfate prior to disposal.

7.4.3 Algal culture systems

Algal culture methods are well established for production facilities where large quantities of high quality microalgae are required for feeding adult broodstock clams, planktotrophic larvae, and juveniles once suspension feeding has been initiated. Algal culture systems established for species other than geoducks are adequate, although attention to quality control cannot be over-emphasized. Most if not all algal production systems suffer at one time or another to bacterial, protozoan, or fungal contamination and adherence to strict hygienic protocols must occur if successful culture operations are the goal. A failure in the algal production facility can be catastrophic to the hatchery. As discussed above with respect to general hatchery conditions, the hatchery infrastructure must include the capability to produce large quantities of 1 micron filtered and UV treated seawater on a routine basis. For algal culture generally, seawater is further filtered by cartridge filtration to either 0.5 or 1.0 micron, sanitized with chlorine (at least 10 ppm) for 4 hours and neutralized with the appropriate amount of sodium thiosulphate for batch algal cultures in excess of 400 L. Smaller volumes of algal media (up to 10 L) are autoclaved (45 min. @ 15 lbs) prior to the addition of algal inoculate.

Most bivalve hatchery facilities have the capability of producing batch cultures of microalgae on a daily basis. The process involves several steps. Test tube volumes of axenic algae are typically procured from commercial suppliers or isolated from native populations of microalgae. The primary cultures are maintained under long-term storage under reduced light and sterile conditions with a portion redirected for production purposes. Production cultures are amplified in volume over a number of days (species specific) by sequentially inoculating increasingly larger volumes of algal media with clean algae. Media utilized by bivalve hatcheries is typically composed of nitrogen, phosphorus, iron, other trace metals (Cu, Zn, Co, Mn, Mo), vitamins (biotin, B-12 and thiamin), and silica if diatoms are being reared. Guillard's F/2, F, 2F or 4F formulations (Guillard 1975) are all used at one time or another for different algal species, again with the addition of silica for growing diatoms. Algal media is produced by the addition of a nutrient formulation to filtered and sanitized seawater. Once inoculated with a healthy (e.g. cultures undergoing rapid multiplication of individual algal cells) algal culture, batch cultures are typically reared under continuous light, although various light regimes may be used to simulate native algal growth conditions. A short lag phase followed by a steep exponential phase until cells either deplete the nutrients or become light limited and the rate of cell divisions begin to slow is the ideal goal for algal production. Excellent nutritional quality of algal cultures may be attained if cultures are nearing or have just attained the stationary phase of growth. Growth rate and qualitative aspects of marine microalgae are dependent on precise culture conditions utilized for production, and these vary by species and the culture facility.

The control of reproduction in marine bivalves remains a critical step in the culture of geoducks, and the quality and quantity of food provided to adults has critical implications for fecundity, gamete quality, and larval vitality. During oogenesis in bivalves generally, the oocytes may receive their lipid reserves both directly from the food and by transfer from stored glycogen reserves in other tissues including the digestive gland and adductor. It is clear from a number of studies that lipid quantity and quality is important for both eggs (Soudant et al. 1996a, 1996b) and developing embryos (Lu et al. 1999). Triglycerides in particular form the energy reserve and source for essential fatty acids for young larvae prior to initiating planktotrophy (Holland and

Spencer 1973, Gallagar et al. 1986, Whyte et al. 1990). Deficiencies in essential fatty acids in bivalve larvae and seed have been the focus of recent research (see Knauer and Southgate 1997), as a number of studies have tried to define the role of highly unsaturated fatty acids (HUFA) in marine bivalves. Species-specific differences among bivalves likely exist in the capacity to lengthen and desaturate 18:3n3 into 20:5n3 and 22:6n3. This capacity is low in *Crassostrea gigas* (Waldock and Holland 1984) and *Pecten maximus* (Delaunay et al. 1993), and unknown for most species including geoducks. However, the requirement for both C20:5n3 and C22:6n3 appears to be important for juveniles (Langdon and Waldock 1981) and larvae, generally (Helm et al. 1991, Marty et al. 1992).

The capability of altering algal biochemical composition by manipulating culture conditions has received considerable attention in recent years. Fatty acid content may be varied in some algal species by altering nutrient regimes (Enright et al. 1986), irradiation (Thompson et al. 1986), temperature (Redalje and Laws 1983) and the timing of harvest (Whyte et al. 1989).

Adult geoduck broodstock during spawning attempt

In summary, biochemical constituents may be varied by the type of culture media utilized, the strain of algae grown, and conditions of light, temperature, availability of carbon dioxide, mixing rate, and other parameters. Modifying the culture conditions such as limiting specific nutrients, light levels, and temperature, may alter biochemical constituents such that nutrition may be enhanced. Algal species utilized for the production of geoducks include the diatoms (Bacillariophyceae), *Chaetoceros calcitrans*, *Chaetoceros gracilis*, *Skeletonema costatum*, the golden-brown flagellates (Prymnesiophytes) *Isochrysis galbana* (T-iso clone) and *Pavolova lutheri*, high lipid strains of *Tetraselmis striata* (Prasinophyte) and *Rhodomonas salina* (3C) Rhodophyte among others.

Excellent references exist for growing microalgae on a large scale, so that specific production details will not be presented here (see Bourne et al. 1994).

7.5 Hatchery production of geoducks

7.5.1 Broodstock collection, maturation, and spawning techniques

Broodstock collections for geoducks are made at intervals over the late fall and winter months to ensure that adequate numbers of male and female clams are available for use. Because possible genetic interactions between farmed and wild stocks of geoducks may occur and as a precaution suggested by WDFW biologists, broodstock

Spawning female geoduck (*Panopea abrupta*)

clams for hatchery use at Taylor Resources, Inc. are carefully selected from the same geographic region where seed will be subsequently planted. For example, broodstock from southern Puget Sound is typically utilized for seed production destined for planting on southern Puget Sound intertidal beaches. Once geoducks are returned to the hatchery facility, they are carefully scrubbed clean of any epibionts and packed tightly in an upright position into plastic milk crates. The number of clams per crate depends entirely on the size of the clams collected. Crates are placed into 400 L volume black polyethylene fish totes supplied with sand-filtered continuous flowing seawater maintained at ambient temperature (10-12 °C) for several weeks prior to a spawn attempt. Supplemental food is supplied to individual totes via feed lines, and algal food concentrations are maintained at approximately 10 – 30 million cells per L. Maintenance of broodstock consists of emptying, cleaning, and refilling totes every few days as biodeposits produced by the clams build up. Otherwise, very little maintenance of broodstock is required.

Techniques for the maturation of broodstock in a commercial hatchery setting have been generally adapted from those used for geoducks and other bivalves (see Goodwin and Pease 1989, Beattie 1992, Russell and Keely 1994), and modified at the Taylor Resources shellfish hatchery. In geoducks, sexes are reported to be separate, and no hermaphrodites have been observed (Goodwin 1973, 1976). In the wild, gametogenesis in adults is initiated in the early fall and continues over the late fall and winter months as ripe gametes are normally observed between March and July with spawning normally occurring between April and July in Pacific Northwest waters (Andersen 1971, Goodwin 1973). Following several weeks of conditioning with supplemental feed and as geoducks enter the window for the normal maturation of gonads (December through April), spawning attempts are made at regular intervals in order to supply larval tanks. A typical spawning attempt involves first draining the polyethylene tote and removing bins of geoducks, rinsing clams, and refilling totes with filtered seawater. As totes are refilling, large quantities of microalgae are added to the totes in order to: 1) increase the temperature in the tote several degrees, and 2) supply clams with a large amount of microalgae. The combination of thermal shock and increased food supply typically induces several to many males to initiate the shedding of gametes. Females typically initiate spawning soon thereafter. Once individual clams begin to spawn, individuals are separated and placed singly into 10 L polyethylene buckets or 100 L polyethylene tanks and encouraged to continue spawning. Once adequate numbers of males and females have produced gametes, eggs are typically combined from all the females and fertilized from a mix of sperm from all the males producing gametes. Equal contributions of sperm from individual males are routinely sought. Typical numbers of spawning clams contributing to a commercial spawn attempt are 8-20 females and a similar number of males whenever possible.

7.5.2 Larval rearing techniques

Fecundity in individual clams is high, although geoducks are dribble spawners and females generally shed between 5 -20 million eggs per spawning episode (Strathmann 1987, E. Jones and J.P. Davis unpublished observations). Larval development in geoducks has been described by Goodwin (1973), Strathmann (1987), and King (1985). Development of fertilized geoduck eggs is strongly dependent on water temperature, with the veliger (Prodissoconch I) stage (110-120 µm shell length) reached approximately 48 hours post fertilization at 16 °C (Goodwin 1973, Goodwin and Pease 1989). The prodissoconch II stage (165 µm) is reached with full umbone development at about 16 days. Modifications of the general rearing protocols for geoducks described above have been more recently developed at the Taylor Resources hatchery facility over the last five years. Larval cultures (40,000 L) may be initially stocked at a density of at least 100 million embryos. Water changes are accomplished five days following fertilization, and thereafter at four-day intervals until the larvae reach setting size with attendant crawling behaviors at 19-20 days. Geoducks do not exhibit an eye spot (ocelli) when they reach the size and age for setting as is the case for many bivalve larvae, however they do possess this unpigmented structure. Feeding of larvae occurs twice daily and is maintained at 15 million cells per L for the duration of the larval period, except near settlement when amounts of microalgal feed is increased as needed. Food levels in tanks are monitored utilizing an electronic particle sizer and counter. Microalgal foods utilized for geoduck culture include a predominance of *Isocrysis galbana* (T-iso) and *Chaetoceros calcitrans* during the initial 10 days. Older cultures (11-20 days) are often supplemented with larger diatoms (*Chaetoceros gracilis* and *Skeletonema costatum*) and *Rhodomonas salina*. Stocking densities of larval geoducks range from over 10,000 larvae per L at the start to less than 1000 larvae per L at the pediveliger stage. One 40,000 L tank easily supplies adequate numbers of juveniles so that higher larval densities, while possible to achieve, are not generally sought.

7.5.3 Post settlement rearing techniques

The dissoconch stage (post-larval) stage is reached between 16 and 35 days post fertilization (350-400 µm), and is characterized by metamorphosis from a swimming larvae and includes the shedding of the velum and settlement and attachment onto a benthic substrate using bysuss threads (Goodwin and Pease 1989). Plantigrade geoducks are characterized by pedal palp feeding as clams utilize the ciliated foot to crawl around and turn over surrounding substrates, picking up algae and detrital particles in the process (Goodwin, et al. 1979). Food particles retained on the foot by this behavior are returned to the labial palps and subsequently ingested (Goodwin 1973a, King 1985, Russell and Keely 1995). At the Taylor Resources facility, competent larvae ready to settle and metamorphose are typically produced in 18-19 days at 14 °C, however this period has been reduced to 14 days on at least several occasions. Competent larvae are placed into primary nursery systems that consist of 3-bin upwell/downwell boxes and supplied filtered (1 micron) seawater at 15-17 °C and cultured microalgae. Pediveliger geoducks are placed into individual screen silos at a stocking density of approximately 150,000 pediveligers per 20 " diameter silo, or 450,000 per upwell/downwell box. Silos are placed on downwell mode and maintained for several days until clams have

Upwell/downwell system used for setting pediveligers metamorphosed and attached with byssal threads to the screens. At this point, clams may be handled and removed with a gentle flow of filtered seawater and placed into secondary nursery systems. These consist of large screens filled with clean, washed sand supplied with under-substrate plumbing designed to generate a slight downwelling effect. Recently metamorphosed clams are introduced to these sand-based nursery systems, supplied with filtered seawater and clean microalgae until large enough for tertiary field nursery systems. Tertiary systems consist either of large outdoor tanks or totes similarly supplied with a similar sand substrate and flowing seawater, or field based "kiddiepools" supplied with clean sand and a mesh cover to eliminate predators that are placed onto the low intertidal beach. Tertiary systems are supplied with small geoduck seed and densities adjusted as needed to supply clams having a nominal valve length of 5 mm and ready to plant into intertidal tubes.

Costs of producing 5 mm shell length geoduck seed exceed those for the rearing of other bivalve seed; seed prices over the last five years have ranged between 10 and 20 cents each. These costs reflect a significant expense associated with growing geoduck seed to a size large enough to plant in intertidal tubes (at least 5 mm in shell length).

8. DEVELOPMENT OF AQUACULTURE PRODUCTION SYSTEMS FOR CULTURED GEODUCK (PSI, Andrew Suhrbier, Aimee Christy, and Dan Cheney)

Panopea are naturally distributed in sandy, subtidal locations worldwide. Commercial markets exist for *P. abrupta* along the Pacific Coast of North America, *P. japonica* in Korea and Japan, *P. zelandica* in New Zealand, and *P. abbreviata* in Argentina. The commercial geoduck fishery is relatively new for many countries. As it gains momentum, a better understanding of geoduck life history and ecology is required (Jeffs 2003, Ciocco 2000). Efforts are currently underway in all of these countries to improve the state of knowledge regarding geoduck growth rates, life expectancy, reproduction, larval development, and species distribution (Breen et al.1991, Kim et al. 1991, You et al. 1993, Jo et al. 1995, Ciocco 2000, Gribben et al. 2003).

8.1 Farm site development and predator protection

8.1.1 Washington

Much of the information in this subsection regarding the development of predator exclusion devices is also discussed in subsection 3.3 under predator-prey interactions, but is retained here nonetheless for readers who may only refer to specific portions of this document. The WDFW has been actively culturing geoduck since the 1970s. The clean, well-protected, nutrient rich waters of Puget Sound were thought to have huge potential in terms of increasing the production of geoducks (Westley 1978). Early larval and juvenile culture techniques were developed by the WDFW Point Whitney Laboratory (also known as the Point Whitney Hatchery). The number of available 10 mm seed grew into the millions in the 1980s, and to 18 million from 1987 to 1990 (Beattie 1992). Goodwin and Pease (1989) stated that as of 1989, WDFW and the WDNR wanted to be able to seed 30 million geoducks over 160 to 200 hectares, annually. The now closed Point Whitney Shellfish Hatchery was producing geoduck seed up to year 2000. Planted hatchery geoducks were thought to be harvestable in 4 to 5 years. A major WDFW goal was to restock public beaches for recreational harvest. WDFW started the Intertidal Shellfish Enhancement Project in 1988. Small portions of the Point Whitney seed may have been utilized by the enhancement project to conduct test planting trials (Caffey et al. 2001). The hatchery side of the process was in full operation, but an increase in survivorship was still needed.

Most of the Point Whitney seed was hand sprinkled from boat, diver, or by scattering apparatus in an effort to enhance geoduck populations in subtidal areas. Surveys of the seeded areas later revealed low average survivorship, less than 1 percent (Beattie et al. 1995). This low survival was attributed to seed predation, by a myriad of creatures, which had access to exposed geoducks for long periods of time, 15 minutes to an hour, while being planted (Cole et al. 1992). Adult geoducks suffer predation as well (Goodwin and Pease 1989); although low, it lowers the overall survival rate of planted geoducks. Bradbury (1989) stated that in order for the outplanting program to be cost effective survival rate had to be at least 5%. Bradbury (1989) also noted that seasonality, seed density and size, and location of adult geoducks may affect survival rate.

Predation experiments showed that crabs (*Cancer productus* and *Cancer gracilis*) consumed 30 to 40% of all planted seed in a 48 hour period. Flatfish and starfish were also considered potential predators. The use of PVC tubes (1' long, 4-6" diameter) and tree planting cones proved to be effective in decreasing mortality. The PVC tube method was introduced by WDFW staff and was quickly adopted by commercial growers (Beattie 1998). Survival increased to 20 to 70% using PVC and 20% using cones (Beattie et al. 1995). A study in 1991 revealed 40% survivorship in a planting on a Washington State Parks and Recreation beach (Beattie 1998). Covering the seafloor with netting where geoducks were just seeded proved to be effective in only 1 out of 4 trials by WDFW (Shuman and Roberts 1989). Protecting geoducks from predators proved to be very labor intensive and expensive. To ameliorate labor costs, volunteers have been utilized to enhance recreational beaches under a joint effort of WDFW and Washington SeaGrant. As of 1998, over 38,000 geoducks had been planted, using 1,400 volunteer hours. Volunteers were also used to take out predator exclusion devices and to patrol grow-out areas for pollution and human predators (King and Beattie 1998).

The durability of the geoduck seed's shell has also been a factor in survivorship. Studies conducted in the early 1990s indicated that seed with broken shells suffered increased mortality (90%) compared with intact seed (37%) (Velasquez 1992b). A study by Velasquez (1993) revealed that lower shell thickness could be a result of high benthic organics and high water temperatures in seed nurseries. Shell thickness also tended to vary greatly from nursery groups.

An intermediate step between the hatchery and growout site was established by WDFW to combat high growout mortalities. This nursery phase enabled the seed to increase in size before outplanting, which in turn increased survival after outplanting (Leitman 1989). In WDFW trials, survivorship inside the nursery tubs covered with netting was excellent, reaching up to 100% (Shuman and Roberts 1989).

Private companies, seeing the high value of geoduck in the Asian market, started planting significant numbers of geoduck seed in intertidal areas in the 1990s. WDFW encouraged new geoduck farms, saying they could supply millions of seed (Anonymous 1997). Premium geoducks were thought to be getting up to $10 to 12 per pound (Chew 2000). On average, geoducks were commanding $5 per pound from commercial harvesters (Anonymous 1997). Early experiments were conducted by Dahman's Shellfish Co. and Taylor Shellfish farms. Dahman's Shellfish saw raising geoducks as a way to utilize intertidal beds not suitable for Manila clams or oysters. Experiments by Dahman's Shellfish enabled them to perfect their own hatchery operations and revealed that seeding was time consuming. Taylor Shellfish evaluated two predator control techniques: car cover netting and PVC tubes with netting. Results showed that while time consuming initially, the use of PVC tubes was more advantageous. Tubes provided less maintenance and greater survival rates (Phipps 1998). By 2000, Taylor Shellfish Farms was planting 2 million seed a year and expecting an initial harvest in 2002 (King 2000).

8.1.2 British Columbia

British Columbia started their own version of geoduck enhancement in the early 1990s looking at nursery and growout methods (Heath 1995). Broodstock was first collected in 1993 from Marina Island BC and now is collected in Georgia Strait and the west and north coasts of Vancouver Island. As early as 1994, Underwater Harvester's Association (UHA) and Fan Seafoods have funded an enhancement program to raise and plant hatchery juvenile geoducks into existing wild geoduck beds (Mylchreest 2003). As of 1999, the Island Scallops hatchery was producing geoduck seed and the UHA had a geoduck planting machine that could plant close to 50,000 seed per day (Clapp 2000). There are now three hatcheries in British Columbia attempting to produce or have the capability to produce geoduck seed. Geoducks are being planted and a few are being harvested by Fan Seafoods in experimental aquaculture sites on provincial land at Marina, Savary, and Texada islands. Sites in the Strait of Georgia are currently seeded by the UHA for enhancement. The UHA wants to expand enhancement efforts to the west coast of Vancouver Island. Fisheries and Oceans Canada have yet to find impacts from enhancement on the wild fishery (Mylchreest 2003).

The UHA took little over a year to complete a working initial design of the seeding machine. The hydraulic machine was then put under frequent trials to perfect efficiency and to increase seed survival. Using the machine, geoducks are planted below the sediment surface in order to protect them from predators. Skog (1998) reported that as of 1998 seeding still needed perfecting. Survival was considered to be low and surveys still needed to be done to effectively assess survival rates. In 2000, Wray (2000) reported that survival was variable from one planting site to the next but that overall results were deemed encouraging by the UHA. With the advent of the seeding machine the UHA hoped that 30% of harvested geoducks will eventually come from planted stocks (Skog 1998). A 3 to 5 year time frame is expected for planted geoducks to reach harvest size stated Holmyard (2000) in an interview with UHA president Bob Saunders.

8.1.3 New Zealand

New Zealand scientists looking at geoduck farming and its potential profitability in the Pacific Northwest decided to look into New Zealand geoduck aquaculture. New Zealand's geoduck fishery was established in 1988 and has since taken a more cautious approach towards harvesting wild stocks due to the species' slow growth rate (Jeffs 2003). Comparisons between the life history of commercially harvested *Panopea zelandica* and *Panopea abrupta* show similarities and differences (Breen et al. 1991, Gribben et al. 2003). *P. zelandica* appears to be smaller and shorter-lived than *P. abrupta*, with a mean shell length of 110.08 ± 12.7 mm, ranging from 61-145 mm, compared to 150 mm for *P. abrupta*. The life span of *P. zelandica* averages 12-13 years with a maximum life span of 34 years as opposed to 28-61 years for *P. abrupta*, with the oldest geoduck recorded to be 146 years. Growth rates are similar for both species with the most rapid growth occurring in the first 10 years (Breen et al. 1991).

Development of the New Zealand geoduck fishery spurred a study by Gribben and Hay (2003) to look at larval development of *Panopea zelandica*. Larval development between *P. zelandica* and *Panopea abrupta* is similar in that trochophores develop within 12 hours and D-stage larvae within 24 hours under hatchery conditions (Gribben et al. 2003). However, *P. zelandica* larvae demonstrate the ability to settle sooner and at a smaller size. Larvae settled after 16 days at a shell length of c. 247 µm compared with 25-30 days at a length of c. 350 µm for *P. abrupta* (Gribben et al. 2003). The report suggested that a startup commercial geoduck hatchery could produce geoduck seed fairly easily.

8.2 Processing

8.2.1 Washington

In the early 1970s in an effort to expand the geoduck market, the four to five small processors in Washington State asked NOAA's Pacific Fishery Products Technology Center in Seattle to help produce a geoduck steak. Minced geoduck was bound together using rockfish flesh and common food ingredients. The resulting 1/4 to 1/2" thick portions were better than previously available versions and held together while deep-fat and pan frying (Miyauchi et al. 1973). Little has been published regarding processing geoducks in Washington.

8.2.2 British Columbia

UHA members abide by a market approval protocol that is designed to reduce the amount of illegally caught geoducks entering the market. All geoducks from harvest to delivery are required to be packed in clean cages, distributed by the UHA, which are made from approved material weighing less than 5 lbs. Detailed government approved logbooks containing independently validated catch weight information must be kept by each individual harvester. Copies of pertaining logbook information must accompany the product to a federally registered distributor or processing plant (Agriculture and Agri-Food Canada 2001).

In Canada, each federally registered fish processor must implement a Quality Management Program (QMP), based on Hazard Analysis and Critical Control Point (HACCP) protocols. The QMP ensures that products leaving the plants onto the marketplace meet regulatory requirements and are safe to eat (Agriculture and Agri-Food Canada 2001).

Geoducks are a valuable commodity in Canada, dominating all other shellfish fisheries. As of 2000, the total landed value of geoduck in Canada reached $41 million Cnd. Most geoducks are sold to China and Hong Kong, where geoduck has been the highest value export from British Columbia in recent years. Prices for geoduck products mirror supply and demand trends for each country. Supply from Canada has stabilized in recent years at 4 million pounds per year. In order to supply market demands in Asia, live geoducks are shipped by next day air from distributors in styrofoam crates with cool packs and wet food-grade paper dividers. Other less valuable geoduck products are also sold. Dried body meat is commonly used for soups and frozen siphon meat is vacuum packed for convenience (Agriculture and Agri-Food Canada 2001).

8.2.3 Korea

The Korean geoduck (*Panopea japonica*) has been considered as a fast food option in Korea in recent years. The monthly composition variation and frozen storage stability of the Korean geoduck was explored by You et al. (1993) to determine ideal harvest times and storage options. For a flavor suitable for Korean tastes, lipid and glycogen studies revealed that harvest time should be in July or August. Blanching the edible portion of the geoduck before freezing was found to maintain freshness.

8.3 Washington health considerations

The health of the farmed geoduck is also of importance. Hatchery operations have intensified over the years to accommodate the increased need of geoduck seed. With intensification, new health and disease problems can arise such as bacterial mats, which can cause debilitating infections in geoduck juveniles. Elston (1998) thought it was possible to counter such health and disease problems by using proper health management plans.

Paralytic shellfish poisoning (PSP) may be a consideration in geoduck site selection for some geographic locations. Since the late 1980s, *Alexandrium catenella*, the organism responsible for PSP toxicity, has expanded its range throughout Puget Sound (Nishitani and Chew 1988). Geoducks, similar to other bivalves, ingest toxic cells while filter feeding and periodically reach concentrations unsafe for human consumption. Washington State Department of Health regulates PSP in shellfish and initiates harvest closures when tissue concentrations exceed 80 µg STXeq/100 g. PSP was once believed to have no impact on the geoduck fishery since toxins accumulate primarily in the viscera (Nishitani and Chew 1988). It is now understood that this portion is not always discarded prior to processing.

Dinoflagellate blooms along the Pacific Coast of North America from Alaska to California tend to be most abundant in summer with the highest PSP toxin levels occurring in July and August (Horner et al. 1997). Dinoflagellates prosper in shallow bays with thermally induced stratification, adequate macronutrients, and little vertical mixing during summer months enabling cells to reach high concentrations (Rensel 1993). At the same time, currents and winds are responsible for mixing toxic cells deeper into the water column making them available to geoducks (Curtis et al. 2000).

Research conducted at two sites in Puget Sound found that PSP toxin was both higher and more variable in geoducks harvested at 7 m depth compared to 17 m depth. Suspected reasons for higher toxicity at the shallow depth include increased availability of food and exposure to cells via vertical mixing. The authors recommend that farmers located in regions that typically encounter PSP, culture geoduck in deeper waters and consider harvesting from these zones during PSP seasons (Curtis et al. 2000).

Little research has been conducted on geoduck toxicity induced by the ingestion of *Alexandrium catenella* cysts. Cysts have been known to exhibit higher toxicity than the motile, planktonic form of the cell (Dale 1978). *A. catenella* form dormant cysts which overwinter in surface sediments where they are buried, ingested by invertebrates including shellfish, or persist to later germinate during favorable environmental conditions. Cysts are also reintroduced to the water column by currents or other types of disturbance such as dredging or harvesting. Research conducted along the Brittany coast in France found the spatial distribution of cysts to correlate with toxic events in upcoming summer months (Erard-Le-Denn 1993).

9. PRELIMINARY IDENTIFICATION OF RESEARCH NEEDS

Geoducks are suspension-feeding bivalves characterized by a complex life cycle where pelagic larvae are produced from highly fecund adults that are very long-lived, sedentary, and occupy a range of marine habitats in Washington State. Data gaps exist in nearly all areas relating to reproduction, recruitment, and genetic interactions as well as predator-prey relationships and community and ecosystem interactions. Specific research questions as they relate to resolving data gaps are summarized below.

9.1 Reproduction, recruitment, and genetic interactions

- What factors influence settlement (biotic, abiotic, conspecific)?

- What effect does commercial harvest have on subsequent settlement?
- Do deep water geoducks, lacking environmental stimuli known to affect shallow populations, undergo gonadogenesis and spawn?
- How long do spawned gametes remain viable?
- At what age do geoducks of each sex mature? What are the sex ratios of geoducks during the first 10 years? Are geoducks gonochoristic or protandrous hermaphrodites? This information is necessary to understand the level of genetic risk associated with intertidal or subtidal geoduck aquaculture.

9.2 Predator-prey interactions

- What are the densities and distributions of geoduck predators and how do they vary temporally and spatially within Puget Sound?
- How does the spatial distribution of geoducks occurring naturally and in outplanted beds affect the densities and distributions of predators?
- Do predator densities, and thus predation risk to geoducks, vary with respect to tidal elevation?
- How much energetic support do consumers receive from geoducks versus other food sources?
- Are juvenile geoducks at fast-growth sites buried more deeply than clams of the same age at slower-growth sites? Does this translate into increased survival of clams at fast-growth sites compared to slower-growth sites?
- Although siphon-nipping is generally regarded as a form of non-lethal predation, does nipping have greater negative effects on juvenile clams compared to adult clams, and result directly in their death?
- Are waterfowl major predators of juvenile geoducks? Do shorebirds, seagulls, and other types of birds prey on juvenile geoducks?

9.3 Community and ecosystem interactions

9.3.1 Suspension feeding activities and water column effects

- Do high densities of geoducks locally deplete phytoplankton and other suspended materials that in turn impact other suspension feeding animals?
- At what spatial or temporal scales do these possible water column effects operate? How do changes in geoduck density affect these interactions?
- Do high densities of geoducks affect water column clarity and light penetration and therefore increase potential for submerged aquatic vegetation? If so, at what spatial scales do these interactions operate?
- How do geoducks affect dissolved oxygen (DO) and to what extent has low DO affected geoduck distribution?

9.3.2 Sediment interactions

- How are sediment properties changed by material processing by geoducks?
- What are the relationships between rates of suspension feeding and rates of material biodeposition and nutrient fluxes in the vicinity of clams?
- Are nutrient fluxes in pore water associated with the presence of geoducks? How might these effects be influenced by geoduck density?
- Does alteration of the sediment by adult geoducks influence the recruitment of conspecifics or other species (e.g. tube-building polychaetes) that may in turn help to recruit conspecifics to existing adult geoduck aggregations?
- How do planted geoducks affect species diversity and abundance of other benthic organisms?
- What is the optimal sediment composition for both intertidal and subtidal geoducks?

9.4 Farming practices

- Is there a way to depurate geoducks so they will be free of PSP, fecal coliforms, and domoic acid during times of high concentrations?

- What is the optimal tube size for use in predator control?
- Are cockles inside geoduck tubes beneficial to geoduck growth?
- Would the use of PVC or paper tubes work as predator control in subtidal areas?
- What would be an optimal density for subtidal plantings?
- What temperature and salinity are optimal for seed survival during intertidal planting?
- What are siting criteria for setting up a subtidal aquaculture lease?

10. LITERATURE CITED

Ahn, I. Y., R. Malouf, and G. Lopez. 1993. Enhanced larval settlement of the hard clam *Mercenaria mercenaria* by the gem clam *Gemma gemma*. *Marine Ecology Progress Series* 99:51-59.

Agriculture and Agri-Food Canada. 2001. Geoduck (Web page). 2001, May 1. Accessed 2004 Jan 8. Available at http: atn-riae.agr.ca/seafood/geoduck-e.htm.

Ambrose, Jr., W. G. 1984. Influences of predatory polychaetes and epibenthic predators on the structure of a soft-bottom community in a Maine estuary. *Journal of Experimental Marine Biology and Ecology* 81:115-145.

Ambrose, Jr., W. G. 1991. Are infaunal predators important in structuring marine soft-bottom communities? *American Zoologist* 31:849-860.

Andersen, A. M., Jr. 1971. Spawning, growth and spatial distribution of the geoduck clam, *Panope generosa* (Gould) in Hood Canal, Washington. Ph.D. Dissertation, University of Washington, Seattle, Washington.

Andre, C. and R. Rosenberg. 1991. Adult-larval interactions in the suspension feeding bivalves *Cerastoderma edule* and *Mya arenaria*. *Marine Ecology Progress Series* 71:227-234.

Andre, C., P. R. Jonsson, and M. Lindegarth. 1993. Predation on settling bivalve larvae by benthic suspension feeders: The role of hydrodynamics and larval behavior. *Marine Ecology Progress Series* 97:183-192.

Anger, K., U. Rogal, G. Schriever, and C. Valentin. 1977. In-situ investigations on the echinoderm *Asterias rubens* as a predator of soft-bottom communities in the western Baltic Sea. *Helgolaender Wissenschaftliche Meeresuntersuchungen* 29:439-459.

Anonymous. 1997. Giant clam go-ahead. *Fish Farming International* 24:6.

Armstrong, J. L. 1991. Food habits of staghorn sculpin, *Leptocottus armatus*, and their role as predators of juvenile Dungeness crab, *Cancer magister*, in the Grays Harbor estuary, Washington. M.S. Thesis. University of Washington, Seattle, Washington.

Armstrong, J. L., D. A. Armstrong, and S. B. Mathews. 1995. Food habits of estuarine staghorn sculpin, *Leptocottus armatus*, with focus on consumption of juvenile Dungeness crab, *Cancer magister*. *Fishery Bulletin* 93:456-470.

Arnold, W. S. 1984. The effect of prey size, predator size, and sediment composition on the role of predation of the blue crab, *Callinectes sapidus* Rathbun, on the hard clam, *Mercenaria mercenaria* (Linne). *Journal of Experimental Marine Biology and Ecology* 80:207-219.

Barshaw, D. E. and K. L. Lavalli. 1988. Predation upon postlarval lobsters *Homarus americanus* by cunners *Tautolabrus adspersus* and mud crabs *Neopanope sayi* on three different substrates: Eelgrass, mud and rocks. *Marine Ecology Progress Series* 48:119-123.

Beal, B. F. 2000. The importance of temporal and spatial replication of field experiments: Effects of sea-grass cover on the growth and survival of cultured juveniles of the soft-shell clam, *Mya arenaria*, and hard clam, *Mercenaria mercenaria*. *Journal of Shellfish Research* 19:568.

Beattie, H. 1998. Geoducks and the Washington Department of Fish and Wildlife, p. 49-50. *In* T. Nosho (ed.), Clam and Oyster Farming. Washington Sea Grant Program, University of Washington, Seattle, Washington.

Beattie, H. and B. Blake. 1999. Development of culture methods for the geoduck clam in the USA (Washington state) and Canada (British Columbia). *World Aquaculture* 30:50-53.

Beattie, J. H. 1992. Geoduck enhancement in Washington State. *Bulletin of the Aquaculture Association of Canada* 92:18-24.

Beattie, J. H., B. Blake, and D. Herren. 1995. Improving survival of planted juveniles of the geoduck clam (*Panopea abrupta*) using predator exclusion devices. *Journal of Shellfish Research* 14:260.

Black, R. and C. H. Peterson. 1988. Absence of preemption and interference competition for space between large suspension feeding bivalves and smaller infaunal macroinvertebrates. *Journal of Experimental Marine Biology and Ecology* 120:183-198.

Blundon, J. A. and V. S. Kennedy. 1982. Refuges for infaunal bivalves from blue crab, *Callinectes sapidus* (Rathbun), predation in Chesapeake Bay. *Journal of Experimental Marine Biology and Ecology* 65:67-81.

Bohonak, A. J. 1999. Dispersal, gene flow, and population structure. *Quarterly Review of Biology* 74:21-45.

Bourne, N., C. A. Hodgson, and J. N. C. Whyte. 1989. A manual for scallop culture in British Columbia. *Canadian Technical Report of Fisheries and Aquatic Sciences* 1694:215 pp.

Bourque, D, G. Miron, and T. Landry. 2001. Predation on soft-shell clams (*Mya arenaria*) by the nemertean *Cerebratulus lacteus* in Atlantic Canada: Implications for control measures. *Hydrobiologia* 456:33-44.

Bower, S and J. Blackbourn. 2003. Geoduck clam (*Panopea abrupta*): Anatomy, Histology, Development, Pathology, Parasites and Symbionts: Anatomy of the Geoduck clams. URL: http://www-sci.pac.dfo-mpo.gc.ca/geoduck/anatomy_e.htm.

Bradbury, A. 1989. Survival of hatchery-grown geoduck (*Panope abrupta*) seed in Puget Sound, Washington. *Journal of Shellfish Research* 81:318.

Bradbury, A. 1999. The relative abundance of benthic animals and plants on subtidal geoduck tracts before and after commercial geoduck fishing. Appendix 6, Final Supplemental Environmental Impact Statement, State of Washington Commercial Geoduck Fishery, May 23, 2001.

Breen, P. A. and T. L. Shields. 1983. Age and size structure in five populations of geoduc [sic] clams (*Panope generosa*) in British Columbia. *Canadian Technical Report of Fisheries and Aquatic Sciences* 1169:62.

Breen, P. A., C. Gabriel, and T. Tyson. 1991. Preliminary estimates of age, mortality, growth, and reproduction in the hiatellid clam *Panopea zelandica* in New Zealand. *New Zealand Journal of Marine and Freshwater Research* 25:231-237.

Britton, J. C. and B. Morton. 1994. Food choice, detection, time spent feeding, and consumption by two species of subtidal Nassariidae from Monterey Bay, California. *Veliger* 37:81-92.

Caffey, A., B. Blake, and W. Cooke. 2001. Enhancement efforts on state tidelands by the WDFW intertidal shellfish enhancement project. *Journal of Shellfish Research* 20:1195.

Calkins, D. G. 1978. Feeding behavior and major prey species of the sea otter, *Enhydra lutris*, in Montague Strait, Prince William Sound, Alaska. *Fishery Bulletin* 76:125-131.

Campbell, A., R. M. Harbo, and C. M. Hand. 1998. Harvesting and distribution of Pacific geoduck clams, *Panopea abrupta*, in British Columbia, p. 349-358. *In*: G. S. Jamieson and A. Campbell (eds.), Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. National Research Council of Canada Research Press, Ottawa.

Cantin, M., J. Bedard, and H. Milne. 1974. The food and feeding of common eiders in the St. Lawrence estuary in summer. *Canadian Journal of Zoology* 52:319-334.

Capehart, A. A. and C. T. Hackney. 1989. The potential role of roots and rhizomes in structuring salt-marsh benthic communities. *Estuaries* 12:119-122.

Cheney, D. P. and T. F. Mumford. 1986. Shellfish and seaweed harvests of Puget Sound. Washington Sea Grant, Seattle, Washington.

Chew, K. K. 1989. Manila clam biology and fishery development in Western North America, p. 243-261. *In*: J. J. Manzi and M. Castagna (eds.), Clam Mariculture in North America. Developments in Aquaculture and Fisheries Science, No. 19.

Chew, K. K. 2000. Status of the shellfish industry. *Aquaculture Magazine* 16:64-66

Ciocco, N. F. 2000. The *Panopea* clam. A new fishery resource from the Argentinean Sea. *Infopesca Internacional* 6:36-39.

Clapp, B. 2000. Underwater harvester's association geoduck enhancement program. *Journal of Shellfish Research* 19:620.

Clark, M. E., T. G. Wolcott, D. L. Wolcott, and A. H. Hines. 1999. Intraspecific interference among foraging blue crabs *Callinectes sapidus*: Interactive effects of predator density and prey patch distribution. *Marine Ecology Progress Series* 178:69-78.

Cole, L. R., J. H. Beattie, and K. K. Chew. 1989. Optimal substrate strategy for survival and growth of early juvenile geoducks, *Panope abrupta* in a sand nursery. *Journal of Shellfish Research* 8:411-412.

Commito, J. A. 1982. Importance of predation by infaunal polychaetes in controlling the structure of a soft-bottom community in Maine, USA. *Marine Biology* 68:77-81.

Commito, J. A. 1983. Naticid snail predation in New England: The effects of *Lunatia heros* on the population dynamics of *Mya arenaria* and *Macoma balthica*. *Journal of Shellfish Research* 3:87.

Cooper, K. and B. Pease. 1988. A relationship between selective larval settlement and adult distribution patterns of geoduck clams and the presence of chaetopterid polychaete tube mats in Puget Sound, Washington. *Journal of Shellfish Research* 7:129 (abstract and unpublished manuscript).

Cressman, K. A., M. H. Posey, M. A. Mallin, L. A. Leonard and T. D. Alphin. 2003. Effects of oyster reefs on water quality in a tidal creek estuary. *Journal of Shellfish Research* 22(3):753-762.

Creswell, P. D. and C. L. McLay. 1990. Handling times, prey size and species selection by *Cancer novaezelandiae* (Jacquinot, 1853) feeding on molluscan prey. *Journal of Experimental Marine Biology and Ecology* 140:13-28.

Creswell, P. D. and I. D. Marsden. 1990. Morphology of the feeding apparatus of *Cancer novaezelandiae* in relation to diet and predatory behaviour. *Pacific Science* 44:384-400.

Currens, K. P. and C. A. Busack. 1995. A framework for assessing genetic vulnerability. *Fisheries* 20:24-31.

Curtis, K. M., V. L. Trainer, and S. E. Shumway. 2000. Paralytic shellfish toxins in geoduck clams (*Panope abrupta*): Variability, anatomical distribution, and comparison of two toxin detection methods. *Journal of Shellfish Research* 19: 313-319.

Dale, B., J. Hurst, and C. Yentsch. 1978. Toxicity in resting cysts of the red tide dinoflagellate *Gonyaulax excavata* from deeper water coastal sediments. *Science* 201:1223-1225.

Dame, R. F. 1996. Ecology of marine bivalves: An ecosystem approach. CRC Press Inc., Boca Raton, Florida.

Dean, D. 1981. Predation on juvenile clams by sandworms, p. 72-78. Proceedings of the Eighth Annual Clam Conference. Boothbay Harbor, Maine.

Delaunay, F., Y. Marty, J. Moal, and J. F. Samain. 1993. The effect of monospecific algal diets on growth and fatty acid composition of *Pecten maximus* (L) larvae. *Journal of Experimental Marine Biology and Ecology* 173:163-179.

Doering, P. H. 1982. Reduction of sea star predation by the burrowing response of the hard clam *Mercenaria mercenaria* (Mollusca : Bivalvia). *Estuaries* 5:310-315.

Dumbauld, B. R., D. A. Armstrong, and T. L. McDonald. 1993. Use of oyster shell to enhance intertidal habitat and mitigate loss of Dungeness crab (*Cancer magister*) caused by dredging. *Canadian Journal of Fisheries and Aquatic Sciences* 50:381-390.

Edmands, S., P. E. Moberg, and R. S. Burton. 1996. Allozyme and mitochondrial DNA evidence of population subdivision in the purple sea urchin *Strongylocentrotus purpuratus*. *Marine Biology* 126:443-450.

Eggleston, D. B., R. N. Lipcius, and A. H. Hines. 1992. Density-dependent predation by blue crabs upon infaunal clam species with contrasting distribution and abundance patterns. *Marine Ecology Progress Series* 85:55-68.

Elner, R. W. and R. N. Hughes. 1978. Energy maximization in the diet of the shore crab *Carcinus maenas*. *Journal of Animal Ecology* 47:103-116.

Elston, R., J. Heidel, J. Davis, and D. Cheney. 1998. Intensive bivalve health management. *Journal of Shellfish Research* 17:1280.

Enright, C.T., G. F. Newkirk, J. S. Craigie, and J. D. Castell. 1986. Growth of juvenile *Ostrea edulis* L. fed *Chaetoceros gracilis* Schott of varied chemical composition. *Journal of Experimental Marine Biology and Ecology* 96: 15-26.

Erard Le Denn, E., E. Desbruyeres, and K. Olu. 1993. *Alexandrium minutum*: Resting cyst distribution in the sediments collected along the Brittany Coast, France, p. 109-114. *In* J. J. Smayda and Y. Shimizu (eds.), Toxic Phytoplankton Blooms in the Sea. Elsevier, Amsterdam.

Ertman, S. C. and P. A. Jumars. 1988. Effects of bivalve siphonal currents on the settlement of inert particles and larvae. *Journal of Marine Research* 46:797-813.

Everett, R. A. and G. M. Ruiz. 1993. Coarse woody debris as a refuge from predation in aquatic communities—an experimental test. *Oecologia* 93:475-486.

Fegley, S. 2001. Demography and dynamics of hard clam populations, p. 383-422. *In* J. Kraeuter and M. Castagna (eds.), Biology of the Hard Clam. Elsevier, New York.

Gallagar, S. M., R. Mann, and G.C. Sasaki. 1986. Lipid as index of growth and viability in three species of bivalves. *Aquaculture* 56:81-103.

Glude, J. B. 1964. The effect of scoter duck predation on a clam population in Dabob Bay, Washington. *Proceedings National Shellfisheries Association* 55:73-86.

Goeij, P. de and P. C. Luttikhuizen. 1998. Deep burying reduces growth in intertidal bivalves: Field and mesocosm experiments with *Macoma balthica*. *Journal of Experimental Marine Biology and Ecology* 228:327-337.

Goeij, P. de, P. C. Luttikhuizen, J. van der Meer, and T. Piersma. 2001. Facilitation on an intertidal mudflat: The effect of siphon nipping by flatfish on burying depth of the bivalve *Macoma balthica*. *Oecologia* 126:500-506.

Goodwin, C. L. 1973a. Subtidal geoducks of Puget Sound. State of Washington Department of Fisheries Technical Report 13. Olympia, Washington.

Goodwin, L. 1973b. Effects of salinity and temperature on embryos of the geoduck clam (*Panope generosa* Gould). *Proceedings of the National Shellfisheries Association* 63:93-96.

Goodwin, L. 1973c. Distribution and abundance of subtidal hard-shell clams in Puget Sound, Washington. Washington State Department of Fisheries Technical Report 14. Olympia, Washington.

Goodwin, L. 1976. Observations on spawning and growth of subtidal geoducks (*Panope generosa*, Gould). *Proceedings of the National Shellfisheries Association* 65:49-58.

Goodwin, C. L. 1977. The effects of season on visual and photographic assessment of subtidal geoduck clam (*Panope generosa*, Gould) populations. *Veliger* 20:155-158.

Goodwin, L. 1979. Subtidal clam population survey of Agate Passage. State of Washington Department of Fisheries Report 87. Olympia, Washington.

Goodwin, L. and B. Pease. 1987. The distribution of geoduck (*Panope abrupta*) size, density, and quality in relation to habitat characteristics such as geographic area, water depth, sediment type, and associated flora and fauna in Puget Sound, Washington. State of Washington Department of Fisheries Technical Report No. 102, Olympia, Washington.

Goodwin, L. C. and Pease, B. 1989. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest) Pacific Geoduck Clam. Biological Report 82(11.120), U. S. Fish and Wildlife Service. Olympia, Washington.

Goodwin, C. L. and B. C. Pease. 1991. Geoduck, *Panopea abrupta* (Conrad, 1849), size, density, and quality as related to various environmental parameters in Puget Sound, Washington. *Journal of Shellfish Research* 10:65-77.

Goodwin, C. L. and W. Shaul. 1984. Age, recruitment and growth of the geoduck clam (*Panope generosa*, Gould) in Puget Sound Washington. Washington State Department of Fisheries Progress Report 215. Olympia, Washington.

Goodwin, C. L., W. Shaul, and C. Budd. 1979. Larval development of the geoduck clam (*Panopea generosa*, Gould). *Proceedings of the National Shellfisheries Association* 69:73-76.

Gosnor, K. L. 1979. A field guide to the Atlantic seashore. Houghton Mifflin, Boston, Massachusetts.

Gribben, P. E. and B. E. Hay. 2003. Larval development of the New Zealand geoduck *Panopea zelandica* (Bivalvia: Hiatellidae). *New Zealand Journal of Marine and Freshwater Research* 37:231-239.

Guillard, R.L. 1975. Culture of phytoplankton for feeding marine invertebrates, p. 29-60. *In* P.B. Smith and P.E. Chanley (eds.), Culture of Marine Invertebrates. Plenum Press, New York.

Haddon R, G. Wear, and H. A. Packer. 1987. Depth and density of burial by the bivalve *Paphies ventricosa* as refuges from predation by the crab *Ovalipes catharus*. *Marine Biology* 94:25-30.

Hamm, D. E. and R. S. Burton. 2000. Population genetics of black abalone, *Haliotis cracherodii*, along the central California coast. *Journal of Experimental Marine Biology and Ecology* 254:235-247.

Heath, W. A. 1995. Developments in shellfish culture in British Columbia. *Journal of Shellfish Research* 14:228.

Heck, Jr., K. L. and T. A. Thoman. 1981. Experiments on predator-prey interactions in vegetated aquatic habitats. *Journal of Experimental Marine Biology and Ecology* 53:125-134.

Hedgecock, D. 1994. Does variance in reproductive success limit effective population sizes of marine organisms?, p. 122-134. *In* A. R. Beaumont (ed.), Genetics and Evolution of Aquatic Organisms. Chapman Hall, London.

Helm, M. M., D. L. Holland, S. D. Utting, and J. East. 1991. Fatty acid composition of early non-feeding larvae of the European flat oyster, *Ostrea edulis*. *Journal of the Marine Biological Association of the United Kingdom* 71:691-705.

Herlinveaux, R. H. and J. P. Tully. 1961. Oceanography of Juan de Fuca Strait. *Journal of the Fisheries Research Board of Canada* 18:1027-1071.

Hilborn, R. and C. Walters. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty. Chapman Hall, New York.

Hines, A. H. and T. R. Loughlin. 1980. Observations of sea otters digging for clams at Monterey Harbor, California. *Fishery Bulletin* 78:159-163.

Hines, A. H., M. H. Posey, and P. J. Haddon. 1989. Effects of adult suspension- and deposit-feeding bivalves on recruitment of estuarine infauna. *Veliger* 32:109-119.

Holland, A. F., N. K. Mountford, M. H. Hiegel, K. R. Kaumeyer, and J. A. Mihursky. 1980. Influence of predation on infaunal abundance in upper Chesapeake Bay, USA. *Marine Biology* 57:221-235.

Holmyard, N. 2000. Shellfish farming on the Pacific Coast. *Seafood International London* 15 (10):36-38.

Horner, R. A., D. L. Garrison, and G. F. Plumley. 1997. Harmful algal blooms and red tide problems on the U.S. west coast. *Limnology and Oceanography* 42:1076-1088.

Iribarne, O., D. Armstrong, and M. Fernandez. 1995. Environmental impact of intertidal juvenile Dungeness crab habitat enhancement: Effects on bivalves and crab foraging rate. *Journal of Experimental Marine Biology and Ecology* 192:173-194.

Irlandi, E. A. 1997. Seagrass patch size and survivorship of an infaunal bivalve. *Oikos* 78:511-518.

Irlandi, E. A. and C. H. Peterson. 1991. Modification of animal habitat by large plants: Mechanisms by which seagrasses influence clam growth. *Oecologia* 87:307-318.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner and R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293:629-638.

Jamison, D., R. Heggen, and J. Lukes. 1984. Underwater video in a regional benthos survey, p. 15-17. *In* Proceedings of the Pacific Congress on Marine Technology. Marine Technology Society, Honolulu, Hawaii.

Jassby, A. D., J. E. Cloern and B. E. Cole. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnology and Oceanography* 47:698-712.

Jeffs, A. 2003. Assessment of the potential for aquaculture development in Northland. A report prepared for Enterprise Northland Aquaculture Development Group. NIWA Client Report: AKL2003-012. 245 pp.

Jo, M. K., K. S. Byun, K. B. Lim, S. J. Son, S. J. Lee, C. I. Baik, Y. J. Park, S. H. Choi, J. P. Hong, G. Y. Kim, K. T. Sung, S. C. Lee, and K. S. Kwun. 1995. Distribution and ecology of major shellfishes in the coastal area of Kyongsangbuk-do. *Bulletin of National Fisheries Research and Development Agency Korea* 51:23-66.

Johnson, M. P., A. L. Allcock, S. E. Pye, S. J. Chambers, and D. M. Fitton. 2001. The effects of dispersal mode on the spatial distribution patterns of intertidal molluscs. *Journal of Animal Ecology* 70:641-649.

Johnson M. S. and R. Black. 1984. Pattern beneath the chaos: The effect of recruitment on genetic patchiness in an intertidal limpet. *Evolution* 38:1371-1383.

Jorde, P. E. and N. Ryman. 1995. Temporal allele frequency change and estimation of effective size in populations with overlapping generations. *Genetics* 139:1077-1090.

Juanes, F. 1992. Why do decapod crustaceans prefer small-sized molluscan prey? *Marine Ecology Progress Series* 87:239-249.

Kalin, R. J. 1984. Observations of a feeding method of the Atlantic ribbon worm, *Cerebratulus lacteus*. *Estuaries* 7:179-180.

Kamermans, P. and H. J. Huitema. 1994. Shrimp (*Crangon crangon* L.) browsing upon siphon tips inhibits feeding and growth in the bivalve *Macoma balthica* (L.). *Journal of Experimental Marine Biology and Ecology* 175:59-75.

Karl, S. A. and J. C. Avise. 1992. Balancing selection at allozyme loci in oysters: Implications from nuclear RFLPs. *Science* 256:100-102.

Kim, H. S., Y. J. Park, W. K. Kim, J. W. Chang, and J. D. Kim. 1991. Studies on ecology and growth of *Panope japonica* in shore of Kangwon Province, Korea. *Bulletin of National Fisheries Research and Development Agency Korea* 45:269-282.

Kimmerer, W. J., E. Gartside, and J. J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Marine Ecology Progress Series* 113:81-93.

King, G. 2000. Operations at Taylor Seafood. *Journal of Shellfish Research* 19:575.

King, J. J. 1985. Feeding in post-larval geoducks. MS thesis. University of Victoria, Victoria, British Columbia.

King, J. J. 1986. Juvenile feeding ontogeny of the geoduck *Panope abrupta* (Bivalvia saxicavacea) and comparative ontongeny and evolution of feeding in bivalves. Thesis. University of Victoria, British Columbia. Victoria, Canada.

King, T. and H. Beattie. 1998. Volunteers can do more than dig a duck. *Journal of Shellfish Research* 17:1304.

Knauer, J. and P.C. Southgate. 1997. Growth and fatty acid composition of Pacific oyster (*Crassostrea gigas*) spat fed a microalga and microcapsules containing varying amounts of eicosapentaenoic and docosahexanoic acid. *Journal of Shellfish Research* 16:447-453.

Kozloff, E. 1983. Seashore Life of the Northern Pacific Coast. Douglas and McIntyre, Vancouver.

Kraeuter, J. N. 2001. Predators and predation, p. 441-589. *In* J. N. Kraeuter and M. Castagna (eds.), Biology of the Hard Clam. Elsevier Science, Amsterdam.

Kvitek, R. G. and J. S. Oliver. 1992. Influence of sea otters on soft-bottom prey communities in Southeast Alaska. *Marine Ecology Progress Series* 82:103-113.

Kvitek, R. G., A. K. Fukayama, B. S. Anderson, and B. K. Grimm. 1988. Sea otter foraging on deep-burrowing bivalves in a California coastal lagoon. *Marine Biology* 98:157-167.

Kvitek, R. G., J. S. Oliver, A. R. de Gange, and B. S. Anderson. 1992. Changes in Alaskan soft-bottom prey communities along a gradient in sea otter predation. *Ecology* 73:413-428.

Langdon, C. J. and M. J. Waldock. 1981. The effect of algal and artificial diets on the growth and fatty acid composition of *Crassostrea gigas* spat. *Journal of the Marine Biological Association of the United Kingdom* 61:431-448.

Lawton, P. and R. N. Hughes. 1985. Foraging behaviour of the crab *Cancer pagurus* feeding on the gastropods *Nucella lapillus* and *Littorina littorea*: Comparisons with optimal foraging theory. *Marine Ecology Progress Series* 27:143-154.

Leber, K. M. 1985. The influence of predatory decapods, refuge, and microhabitat selection on seagrass communities. *Ecology* 66:1951-1964.

Leitman, A. R. 1989. The past, present and future of geoduck (*Panope abrupta*) seeding efforts in Puget Sound. *Journal of Shellfish Research* 8:414.

Levinton, J. S. 1971. Control of tellinacean (Mollusca: Bivalvia) feeding behaviour by predation. *Limnology and Oceanography* 16:660-662.

Levitan, D., M. Sewell, and F. Chia. 1992. How distribution and abundance influence fertilization success in the sea urchin *Strongylocentrotus franciscanus*. *Ecology* 73:248-254.

Lipcius, R. N. and A. H. Hines. 1986. Variable functional responses of a marine predator in dissimilar homogeneous microhabitats. *Ecology* 67:1361-1371.

Lu, T.Y., N. J. Blake, and J. J. Torres. 1999. Biochemical utilization during embryogenesis and metamorphosis in the Bay scallop, *Argopectien irradians concentricus* (Say). *Journal of Shellfish Research* 18:425-429.

Mansour, R. A. and R. N. Lipcius. 1991. Density-dependent foraging and mutual interference in blue crabs preying upon infaunal clams. *Marine Ecology Progress Series* 72:239-246.

Mariani, S., V. Ketmaier, and E. de Matthaeis. 2002. Genetic structuring and gene flow in *Cerastoderma glaucum* (Bivalvia: Cardiidae): Evidence from allozyme variation at different geographic scales. *Marine Biology* 140:687-697.

Marty, Y., F. Delaunay, J. Moal, and J. F. Samain. 1992. Changes in the fatty acid composition of *Pecten maximus* (L) during larval development. *Journal of Experimental Marine Biology and Ecology* 163:221-234.

Mauzey, K. P., C. Birkeland, and P. K. Dayton. 1968. Feeding behavior of asteroids and escape responses of their prey in the Puget Sound region. *Ecology* 49:603-619.

McClintock, J. B. and T. R. Robnett, Jr. 1986. Size selective predation by the asteroid *Pisaster ochraceus* on the bivalve *Mytilus californianus*: A cost benefit analysis. *Marine Ecology* 7:321-332.

Menge, B. A. 1982. Effects of feeding on the environment: Asteroidea, p. 521-551. *In* M. Jangoux and J. M Lawrence (eds.), Echinoderm Nutrition. Balkema, Rotterdam.

Miyauchi, D., M. Patashnik, and G. Kudo. 1973. Fish protein used to bind pieces of minced geoduck. *Proceedings of the National Shellfisheries Association* 63:9.

Moberg, P. E. and R. S. Burton. 2000. Genetic heterogeneity among adult and recruit red sea urchins, *Strongylocentrotus franciscanus*. *Marine Biology* 136:773-784.

Moller, P. and R. Rosenberg. 1983. Recruitment, abundance and production of *Mya arenaria* and *Cardium edule* in marine shallow waters western Sweden. *Ophelia* 22:33-55.

Moore, K. A., H. A. Neckles and R. J. Orth. 1996. *Zostera marina* (eelgrass) growth and survival along a gradient of nutrients and turbidity in the lower Chesapeake Bay. *Marine Ecology Progress Series* 142:247-259.

Moore, K. A. and R. L. Wetzel. 2000. Seasonal variations in eelgrass (*Zostera marina* L.) responses to nutrient enrichment and reduced light availability in experimental ecosystems. *Journal of Experimental Marine Biology and Ecology* 244: 1-28.

Morris, R., D. Abbott, and E. Haderlie. 1980. Intertidal Invertebrates of California. Stanford University Press, Stanford, California.

Mylchreest, R. 2003. 2003 Geoduck and horse clam integrated fisheries management plan. Fisheries and Oceans Canada, Vancouver, British Columbia.

Nakaoka, M. 2000. Nonlethal effects of predators on prey populations: Predator-mediated change in bivalve growth. *Ecology* 81:1031-1045.

Nishitani, L. and K. K. Chew. 1988. PSP toxins in the Pacific coast states: Monitoring programs and effects on bivalve industries. *Journal of Shellfish Research* 7:653-669.

Paine, R. T. 1976. Size-limited predation: An observational and experimental approach with the *Mytilus-Pisaster* interaction. *Ecology* 57:858-873.

Palacios. R. 1994. Individual growth and dynamics of living and extinct soft shell clam (*Mya arenaria*) populations in Grays Harbor, Washington, and ecological interactions with Dungeness crab (*Cancer magister*). Ph.D. Dissertation, University of Washington, Seattle, Washington.

Palazzi, D., L. Goodwin, A. Bradbury, and R. Sizemore. 2001. State of Washington Commercial Geoduck Fishery, Final Supplemental Environmental Impact Statement. Washington Department of Natural Resources and Washington Department of Fish and Wildlife, Olympia, Washington.

Pease, B. and K. Cooper. 1986. A relationship between selective larval settlement and adult distribution patterns of geoduck clams and the presence of chaetopterid polychaete tube mats in Puget Sound, Washington. *Journal of Shellfish Research* 7:129.

Pennifold, M. and J. Davis. 2001. Macrofauna and nutrient cycling in the Swan River Estuary, Western Australia: Experimental results. *Hydrological Processes* 15(13):2537-2553.

Perry, M. C. and F. M. Uhler. 1988. Food habits and distribution of wintering canvasbacks, *Aythya valisineria*, on Chesapeake Bay. *Estuaries* 11:57-67.

Peterson, B. J. and K. L. Heck. 2001a. An experimental test of the mechanism by which suspension feeding bivalves elevate seagrass productivity. *Marine Ecology Progress Series* 218: 115-125.

Peterson, B. J. and K. L. Heck. 2001b. Positive interactions between suspension-feeding bivalves and seagrass - a facultative mutualism. *Marine Ecology Progress Series* 213: 143-155.

Peterson, C. H. 1984. Does a rigorous criterion for environmental identity preclude the existence of multiple stable points? *American Naturalist* 124(1):127-133.

Peterson, C. H. and M. L. Quammen. 1982. Siphon nipping: Its importance to small fishes and its impact on growth of the bivalve *Protothaca staminea* (Conrad). *Journal of Experimental Marine Biology and Ecology* 63:249-268.

Phelps, H. L. 1994. The asiatic clam (*Corbicula fluminea*) invasion and system-level ecological change in the Potomac River estuary near Washington, DC. *Estuaries* 17:614-621.

Phelps, S. 1993. Evidence for distinct geoduck gene pools in Washington. Unpublished memo, Washington Department of Fish and Wildlife, Olympia, Washington.

Phipps, B. 1998. Geoduck planting and grow-out trials, p. 56. *In* T. Nosho (ed.), Clam and Oyster Farming. Washington Sea Grant Report, University of Washington, Seattle, Washington.

Powell, E. N., E. E. Hofmann, J. M. Klinck, and S. M. Ray. 1992. Modeling oyster populations I. A commentary on filtration rate. Is faster always better? *Journal of Shellfish Research* 11(2):387-398.

Prezant, R., H. Rollins, and R. Toll. 1990. Dispersal of adult hard clams as an adjunct to larval recruitment. *American Zoologist* 30:89.

Redalje, D. G. and E. A. Laws. 1983. The effects of environmental factors on growth and the chemical and biochemical biocomposition of marine diatoms. Light and temperature effects. *Journal of Experimental Marine Biology and Ecology* 68:59-79.

Rensel, J. 1993. Factors controlling paralytic shellfish poisoning (PSP) in Puget Sound, Washington. *Journal of Shellfish Research* 12:371-376.

Reusch, T. B. H. and S. L. Williams. 1999. Macrophyte canopy structure and the success of an invasive marine bivalve. *Oikos* 84: 398-416.

Ripley, B. 1998. Life history traits and population processes in marine bivalve mollusks. Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Riquelme, C., R. Araya, N. Vergera, A. Rojas, M. Guanita, and M. Candia. 1997. Potential probiotic strains in the culture of the Chilean scallop, *Argopecten purpuratus* (Lamarck, 1819). *Aquaculture* 154:17-26.

Rogers, B. B. and D. A. Rogers. 1989. Can a small moonsnail, *Polinices lewisii*, eat a large clam, *Tapes japonica*? *Northwest Environmental Journal* 5:177-179.

Ross, D. J., C. R. Johnson, and C. L. Hewitt. 2002. Impact of introduced seastars *Asterias amurensis* on survivorship of juvenile commercial bivalves *Fulvia tenuicostata*. *Marine Ecology Progress Series* 241:99-112.

Rowell, T. W. and P. Woo. 1990. Predation by the nemertean worm, *Cerebratulus lacteus* Verrill, on the soft-shell clam, *Mya arenaria* Linnaeus, 1758, and its apparent role in the destruction of a clam flat. *Journal of Shellfish Research* 9:291-297.

Russell, Jr., H. 1972. Use of a commercial dredge to estimate a hard shell clam population by stratified random sampling. *Journal of the Fisheries Research Board of Canada* 29:1731-1735.

Russell, S. and N. Keeley. 1995. The geoduck clam (*Panopea generosa*). Malaspina University College, in conjunction with IEC and FAN Seafoods, 49 pp.

Saila, S., J. Flowers, and M. Cannario. 1967. Factors affecting the relative abundance of *Mercenaria mercenaria* in the Providence River, Rhode Island. *Proceedings of the National Shellfisheries Association* 57:83-89.

Saila, S. and T. Gaucher. 1966. Estimation of the sampling distribution and numerical abundance of some mollusks in a Rhode Island salt pond. *Proceedings of the National Shellfisheries Association* 56:73-80.

Sastry, A. 1979. Pelecypoda (Excluding Ostreidae), p. 113-292. In A. Giese and J. Pearse (eds.), Reproduction of Marine Invertebrates, Vol V. Plenum Press, New York.

Seitz, R. D., R. N. Lipcius, A. H. Hines, and D. B. Eggleston. 2001. Density-dependent predation, habitat variation, and the persistence of marine bivalve prey. *Ecology* 82:2435-2451.

Shaklee, J. B. and P. Bentzen. 1998. Genetic identification of stocks of marine fish and shellfish. *Bulletin of Marine Science* 62:589-621.

Shaul, W. and L. Goodwin. 1982. Geoduck (*Panope generosa*: Bivalvia) age determined by internal growth lines in the shell. *Canadian Journal of Fisheries and Aquatic Sciences* 39:632-636.

Shuman, F. R. and T. L. Roberts. 1998. Biological feasibility of intertidal aquaculture of the geoduck clam, (*Panope generosa*). *Journal of Shellfish Research* 8:416.

Skog, M. 1998. Geoduck fishermen ensure their own future. URL: www.geocities.com.

Sigurdsson, J., C. Titman, and P. Davies. 1976. The dispersal of young post-larval bivalve molluscs by byssus threads. *Nature* 262:386-387.

Skalamera, J. P., F. Renaud, M. Raymond, and T. de Meeus. 1999. No evidence for genetic differentiation of the mussel *Mytilus galloprovincialis* between lagoons and the seaside. *Marine Ecology Progress Series* 178:251-258.

Skilleter, G. A. 1994. Refuges from predation and the persistence of estuarine clam populations. *Marine Ecology Progress Series* 109:29-42.

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

Sloan, N. A. and S. M. C. Robinson. 1983. Winter feeding by asteroids on a subtidal sandbed in British Columbia. *Ophelia* 22:125-140.

Smith, T. E., R. C. Ydenberg, and R. W. Elner. 1999. Foraging behaviour of an excavating predator, the red rock crab (*Cancer productus* Randall) on soft-shell clam (*Mya arenaria* L.). *Journal of Experimental Marine Biology and Ecology* 238:185-197.

Soudant, P., Y. Marty, J. Moal and J. F. Samain. 1996. Fatty acids and egg quality in great scallop. *Aquaculture International* 4:191-200.

Soudant, P., Y. Marty, J. Moal, R. Robert, C. Quere, J. L. Le Coz, and J. M. Samain. 1996. Effect of food fatty acid and sterol quality on *Pecten maximus* gonad composition and reproduction process. *Aquaculture* 143:361-378.

Sponaugle, S. and P. Lawton. 1990. Portunid crab predation on juvenile hard clams: Effects of substrate type and prey density. *Marine Ecology Progress Series* 67:43-53.

Strathmann, M. F. 1987. Reproduction and Development of Marine Invertebrates of the North Pacific Coast. University of Washington Press, Seattle, Washington.

Stephenson, M. D. 1977. Sea otter predation on Pismo clams in Monterey Bay. *California Fish and Game* 63:117-120.

Stevens, B. G., D. A. Armstrong, and R. Cusimano. 1982. Feeding habits of the Dungeness crab *Cancer magister* as determined by the index of relative importance. *Marine Biology* 72:135-145.

Summerson, H. C. and C. H. Peterson. 1984. Role of predation in organizing benthic communities of a temperate-zone seagrass bed. *Marine Ecology Progress Series* 15:63-77.

Tallqvist, M. 2001. Burrowing behaviour of the Baltic clam *Macoma balthica*: Effects of sediment type, hypoxia, and predator presence. *Marine Ecology Progress Series* 212:183-191.

Tamburri, M. N. and R. K. Zimmer-Faust. 1996. Suspension feeding: Basic mechanisms controlling recognition and ingestion of larvae. *Limnology and Oceanography* 41:1188-1197.

Thompson P. A., M. Guo, and P. J. Harrison. 1986. Nutritional value of diets that vary in fatty acid composition for larval Pacific oysters (*Crassostrea gigas*). *Aquaculture* 143: 379-391.

Thompson, D. S. 1995. Substrate additive studies for the development of hardshell clam habitat in waters of Puget Sound in Washington State: An analysis of effects on recruitment, growth and survival of the Manila clam, *Tapes philippinarum*, and on existing species diversity and abundance of existing benthic organisms. *Estuaries* 18:91-107.

Toba, D. R., D. S. Thompson, K. K. Chew, G. J. Anderson, and M. B. Miller. 1992. Guide to Manila clam culture in Washington. Washington Sea Grant Program, University of Washington, Seattle, Washington.

Turner, K. and R. Cox. 1981. Seasonal reproductive cycle and show factor variation of the geoduck clam (*Panope* [sic] *generosa* (Gould) in British Columbia. *Journal of Shellfish Research* 1:125.

Vadopalas, B. and J. Davis. 2004. Optimal chemical triploid induction in geoduck clams, *Panopea abrupta* (Conrad, 1849), by 6-dimethylaminopurine. *Aquaculture* 230:29-40.

Vadopalas, B., L. LeClair, and P. Bentzen. In review. Microsatellite and allozyme analyses reveal genetic differences between spatially distinct aggregations of geoduck clams (*Panopea abrupta*, Conrad 1849). *Marine Biology*.

Van Koeveringe, M. A. H. 1998. Molecular population genetics of British Columbia geoduck clams, *Panope abrupta*, based on mitochondrial DNA sequences. Thesis, Simon Fraser University, Vancouver.

Van Veldhuizen, H. D. and D. W. Phillips. 1978. Prey capture by *Pisaster brevispinus* (Asteroidea: Echinodermata) on soft substrate. *Marine Biology* 48:89-97.

Velasquez, D. E. 1992a. Shell structure and fragility in nursery-reared juvenile geoducks *Panopea abrupta* (Conrad). M.S. Thesis, University of Washington, Seattle, Washington.

Velasquez, D. E. 1992b. Shell fragility in juvenile geoducks (*Panopea abrupta*) and its implications for the geoduck enhancement program. *Journal of Shellfish Research* 11:208.

Velasquez, D. E. 1993. Shell fragility and its implications for the geoduck enhancement program. *World Aquaculture* 24:34-38.

Virnstein, R. W. 1977. The importance of predation by crabs and fishes on benthic infauna in Chesapeake Bay. *Ecology* 58:1199-1217.

Waldock, M. J. and D. L. Holland. 1984. Fatty acid metabolism in young oyster *Crassostrea gigas*: Polyunsaturated fatty acids. *Lipids* 19:332-336.

Wendell, F., J. D. Demartini, P. Dinnel, and J. Siecke. 1976. The ecology of the gaper or horse clam, *Tresus capax* (Gould 1850) (Bivalvia: Mactridae), in Humboldt Bay, California. *California Fish and Game* 62:41-64.

Westley, R. E. 1976. The present status and future outlook of shellfish farming in Puget Sound, Washington. *Proceedings of the National Shellfisheries Association* 66:106.

Whyte, J. N. C., N. Bourne, and C.A. Hodgson. 1989. Influence of algal diets on biochemical composition and energy reserves in *Patinopectin yessoensis* (Jay) larvae. *Aquaculture* 78:333-347.

Whyte, J. N. C., N. Bourne, and N. G. Ginther. 1990. Biochemical changes during embryogenesis in the rock scallop *Crassodoma gigantea*. *Marine Biology* 106:239-244.

Williams, G. D. 1994. Effects of habitat modification on distribution and diets of intertidal fishes in Grays Harbor estuary, Washington. M.S. Thesis, University of Washington, Seattle, Washington.

Wilson, K. A., K. W. Able, and K. L. Heck. 1987. Juvenile blue crab *Callinectes sapidus* survival: an evaluation of eelgrass, *Zostera marina*, as refuge. *Fishery Bulletin* 85:53-58.

Wobber, D. R. 1975. Agonism in asteroids. *Biological Bulletin* 148:483-496.

Wolf, H. de, R. Verhagen, and T. Backeljau. 2000. Large scale population structure and gene flow in the planktonic developing periwinkle, *Littorina striata*, in Macaronesia (Mollusca : Gastropoda). *Journal of Experimental Marine Biology and Ecology* 246:69-83.

Wray, T. 2000. Geoduck fishermen secure their future. *Fish Farming International* 27:36.

Yocom, C. F. and M. Keller. 1961. Correlation of food habits and abundance of waterfowl, Humboldt Bay, California. *California Fish and Game* 47:41-54.

Yonge, C. and T. Thompson. 1976. Living Marine Molluscs. Collins, London.

You, B. J., I. H. Jeong, K. H. Lee, and H. G. Choi. 1993. Quality and storage stability of frozen geoduck *Panope japonica* (A. Adams). *Bulletin of Korean Fisheries Society* 26:549-556.

Zaklan, S. D. and R. C. Ydenberg. 1997. The body size/burial depth relationship in the infaunal clam *Mya arenaria*. *Journal of Experimental Marine Biology and Ecology* 215:1-17.

Zwarts, L. and J. Wanink. 1989. Siphon size and burying depth in deposit- and suspension-feeding benthic bivalves. *Marine Biology* 100:227-240.

11. ANNOTATED BIBLIOGRAPHY (Pacific Shellfish Institute)

Andersen, A. M. Growth of the geoduck clam in Hood Canal, Washington. Proc-Natl-Shellfish-Assoc. 1972; 621. CODEN: Natl. Shellfisheries Association Convention, Seattle (Washington), 20-24 Jun 1971. Abstract: The growth of *Panope generosa* can be described by a von Bertalanffy growth curve, Lt = 22.5 cm (1- sub(e) -0.15t). This was established by examining the growth lines on geoduck shells, by studying length-frequency distributions of geoducks dug at Dosewallips and Big Beef, and by planting and recovering tagged geoducks at Big Beef, Hood Canal, WA. Growth lines on shells were determined to be unreliable indicators of age. The length-frequency distributions revealed 3 distinct yr. classes. The average lengths of these yr classes at various ages provided estimates of the von Bertalanffy growth constants. Although tagging and planting temporarily stopped the growth of tagged geoducks and caused marking checks, some tagged geoducks grew well and these supported the growth curve derived from the length-frequency distributions. Geoducks grew throughout the yr but data were insufficient to quantify seasonal growth rates. Tagged geoducks planted at the -1-ft, -2-ft, -4-ft, and -10-ft tide levels grew at the same rate. The relationship between shell length and total weight is curvilinear. The relationship between total weight and meat wt is rectilinear. In both relationships there is a lot of variation. The average, whole, freshly-dug geoduck consists of (by weight): 28.1 per cent sand and water, 17.4 per cent shell, 12.0 per cent viscera and 42.5 per cent edible meat. A 1-yr-old geoduck lives in a burrow approx. 20 cm deep, has shells approx 3 cm long, and weighs approx 10 g. A 3-yr-old geoduck lives approx 60 cm deep, has shells 10 cm long and weighs 300 g. A 10-yr-old geoduck is nearly full-grown, lives in a burrow 80 cm deep, has shells 17 cm long, and weighs approx 1600 g.

---. Spawning, growth and spatial distribution of the geoduck clam, *Panope generosa* Gould, in Hood Canal, Washington. Res-Fish-Coll-Fish-Univ-Wash. 1972; 1971(355):76. Abstract: An abstract is presented of this Ph. D. thesis. The study was undertaken because of increasing recreational fishing pressure, an imminent commercial fishery, and the lack of previous studies.

---. A study of the geoduck clam, *Panope generosa* Gould. Res-Fish-Coll-Fish-Univ-Wash. 1971; 1970(340):35. Abstract: The study was undertaken to provide scientific information to help form a basis for sound management decisions involving the geoduck fisheries, which are being subjected to increasing commercial and recreational fishing. Results on growth rates, survival rates, age at 1st maturity, spawning season and minimum size taken by sport diggers are summarized.

Anonymous. Market grows for America's giant clams. Fish-News-Int. 1973; 12(11):37-38. Abstract: The harvesting of recently discovered abundant supplies of the beef clam *Panope generosa* in the State of Washington is described. A diver grasps the protruding siphon with one hand, insert a water pump wash-out nozzle alongside and triggers the 40 lb of water pressure which loosens the clam body and helps to lift it from its hole. Difficulties encountered at the depths where harvesting is permitted, and during the winter months, are reviewed. It is reported that the fishery is now stabilizing and there is an increase in the confidence of the market. The density of clams appears to be such that 1 yr after harvesting, ie removal of some specimens, there is no observable change in density. There is restriction which prevents harvesting within 1/4 mile of the shore which makes diving impractically deep in some areas but it is considered that 10% of the coast is harvestable.

---. Giant clam go-ahead. FISH-FARM.-INT. 1997; 24(8):6. Abstract: Farming of giant clams is about to start in the US and Canada, after scientists have laid the groundwork for the cultivation of the geoduck. Now high prices in Hong Kong and elsewhere are providing the incentive a new industry needs. Thanks to its rocketing value, harvesters of wild clam in Washington state in the US and British Columbia in Canada can earn up to US$5/lb. Between 3,000,000 and 8,000,000lb have been collected in recent seasons from Washington's Puget Sound alone. Clam meat is now fetching about $12/lb at retail outlets in the Far East. To encourage start-up farms, Washington State's Department of Fisheries has announced that it can supply millions of geoduck seed. Its Hood Canal and Point Whitney hatcheries are all ready to go into production. Planting experiments using plastic tubing have shown commercial growing is feasible. Potential sites in the huge Puget Sound region are plentiful, officials say.

---. *Panopea* Menard de la Groye, April 1807 (Mollusca, Bivalvia): Proposed conservation and related problems. Z.N.(S.) 1049. BULL.-ZOOL.-NOMENCL. 1983; 40(3):179-183. Abstract: The main object of the present application is the stabilization of the form of the generic name that has hitherto been known by the alternative renderings, *Panope*, *Panopea* and *Panopaea*. The opportunity is taken to seek clarification of the status of certain names involved in the discussion.

Beattie, H. Geoducks and the Washington department of fish and wildlife. Clam-and-Oyster-Farming Nosho,-T.-(Ed.) Washington-Univ,-Seattle-USA-Sea-Grant-Program. 1998; 49-50. CODEN: 7. Conf. for Shellfish Growers: Clam and Oyster Farming, Olympia, WA (USA), 3-4 Mar 1997. Abstract: Prior to 1970, geoducks were strictly an intertidal recreational harvest species. In the late 1960s, diver-biologists from the Washington Department of Fisheries, now the Washington Department of Fish and Wildlife (WDFW), discovered and documented vast reserves of sub-tidal geoducks. In 1970, the commercial fishery for subtidal geoducks began. WDFW assesses subtidal populations of geoducks for number, size and quality. Geoducks are a sedentary natural resource and as such the Department of Natural Resources (DNR) manages the sale of sub-tidal tracts fished by the commercial geoduck fishery. Geoduck distribution: Baja, California to Alaska, from +3 foot tidal height to -400 feet deep. Geoducks can live for more than 100 years. Once harvested, geoducks stocks are slow to repopulate--about 50 years on average. The allowable harvest in Washington state is about 3 million pounds per year, equivalent to 2% of harvestable population. Most geoducks are unavailable for harvest, living either in closed areas or in waters too deep for divers. Geoducks start sexual reproduction at 4 to 5 years old. They spawn periodically from March to July, with each female producing about 40 million eggs over the season. Geoducks grow to a weight of about 2 pounds in five years and reach maximum size in 15 years. The average weight of geoducks harvested from Puget Sound is just under 2 pounds, however geoducks can reach weights of more than 14 pounds. Geoduck culture began on a small scale at Point Whitney in the 1970s. Commercial scale culture started in 1982 under a memorandum agreement between the Department of Fisheries and the Department of Natural Resources. The goal of the project was to double the subtidal commercial harvest of geoducks in 10 years. By 1987, the hatchery was producing 6 million geoduck seed per year. These seed were planted without protection into subtidal areas.

--- (Washington, Univ., Seattle (USA). Sea Grant Program). Recent research on nursery practices for geoducks and mussels.Nosho, T. Y. and Chew, K. K; 1991. Abstract: Nursery methods currently used for geoducks (*Panope abrupta*) and mussels (*Mytilus*) are discussed, including a sand substrate nursery system for geoducks, and Japanese onion sacks filled with twine or rope for mussels.

Beattie, H. and Blake, B. Development of culture methods for the geoduck clam in the USA (Washington state) and Canada (British Columbia). World-Aquaculture . 1999; 30(3):50-53; ISSN: ISSN 1041-5602.

Beattie, H. J. Serial spawning of the geoduck clam (*Panopea abrupta*). ANNUAL-MEETING-OF-NATIONAL-SHELLFISHERIES-ASSOCIATION-PACIFIC-COAST-SECTION -AND-PACIFIC-COAST-OYTSER-GROWERS-ASSOCIATION. 1995: 227. Abstract: Geoduck clams represent a valuable resource both in Washington State and British Columbia. The ex-vessel value of geoduck increased from $.50 per pound to $7.50 per pound from 1987 to the present. The Point Whitney Laboratory has been culturing geoduck since the early 1970's. The standard mode of operation for obtaining gametes was to bring adult animals to the hatchery, hold them for conditioning for 2 to 6 weeks and spawn them once. This entailed using hundreds of animals for each spawn, thousands of animals over the spawning season. Egg take per female was approximately 10 million. The current value of geoduck renders that method impractical; broodstock costs would be exorbitant. Using the same broodstock for more than one spawn would represent a more economical approach. In 1994, we undertook a serial spawning experiment at Point Whitney. Our dive team collected 86 geoducks on 10 February 1994. These animals were held in flowing sea water at 10 degree C and received a supplemental cultured algal diet. On 17 March 1994 we attempted and succeeded with the first spawn. Each week thereafter we attempted to induce spawning with these same animals. The group spawned successfully nearly each week from 17 March through 13 July. The number of males spawning was always more than the number of females. The number of males that spawned each week varied between 4 and 44. The number of females

that spawned varied from 0 to 29. The spawning of females appeared to be cyclical with more individuals spawning every second or third week. Total eggs spawned over the season was over 2.3 billion; one female spawned ten times. (DBO)

Beattie, J. H. Geoduck enhancement in Washington State. [Bourne,-N.;Heath,-W.-eds.]. WORKSHOP-ON-WATER-QUALITY-AND-ALTERNATE-SPECIES-IN-THE-CANADIAN-MOLLUSC-CULTURE-INDUSTRY. 1992; (92-4):18-24. CODEN: Workshop on Water Quality and Alternate Species in the Canadian Mollusc Culture Industry, Vancouver, BC (Canada), 1 Jun 1992. Abstract: The geoduck (*Panopea abrupta*) enhancement project began in 1982. The initial goal was to increase commercial harvest of geoducks in Washington State by 2.3 million kilograms per year. Efforts until 1985 established hatchery techniques. Work from 1985 to 1987 concentrated on developing sand substrate nurseries with capacities up to 8 million seed and since 1987 methods of increasing hatchery output and for expanding nursery capability have been explored. Due to nursery production problems beginning in 1989, considerable work has been done on areas of survival and quality of seed coming from the nursery. Another area of concentration has been subtidal field survival of planted geoduck seed. Small scale experimental hand plants by divers resulted in survival rates exceeding 40%. However, from nearly 18 million broadcast planted seed, survival after 2-3 yr was < 1%, only about a tenth of that expected. Field observations and laboratory experiments suggest that losses are due to predation within the first year.

Beattie, J. H. Geoducks, predators, and volunteers. J.-SHELLFISH-RES. 1992 Vol. 11, No. 2, P. 551. 1992. CODEN: 43. Annu. Meet. Pacific Coast Oyster Growers Assoc. and Natl. Shellfish. Assoc. (Pacific Coast Sect.), (np), 17-19 Sep 1992. Abstract: The geoduck (*Panopea generosa*) enhancement project in Washington, USA began in 1982. By 1987 the program had developed sand substrate nurseries. From 1987 to 1990, the hatchery/nursery produced 18 million seed. The present area of concentration is field survival of planted geoduck seed. From the 18 million broadcast planted seed, survival after 2 to 3 years was less than 1%, only about a tenth of that expected. Field observations and laboratory experiments suggest that these losses are due to predation within the first year after planting. Predators include crabs, starfish and flatfish. Work in 1991 used volunteer labor for intertidal plants on 4 state park beaches. Predator protection devices were made of PVC tubing and plastic screening. Resulting survival ranged from 20% to nearly 70% and averaged about 40% among the beaches tested. Present laboratory and intertidal and subtidal field experiments on predator protection devices include evaluation of tube composition, size, planting density and screening the tops of the tubes.

---. A sand substrate nursery for geoduck clams (*Panope abrupta*). J.-SHELLFISH-RES. 1988. Vol. 7, No. 3, P. 562. 1988. CODEN: 1989 Annu. Meet. of the National Shellfisheries Association, Los Angeles, CA (USA), 12 Feb 1989; ISSN: ISSN 0077-5711. Abstract: The Washington State Department of Fisheries has been working with the hatchery and nursery culture of geoduck clams (*Panope*

abrupta) since the early 1970's. A need for artificial supplementation of geoduck stocks became obvious in the mid-1970's when surveys of commercially harvested subtidal beds indicated low levels of recruitment. Implementation of sand substrate nurseries has resulted in an increase in annual production from a few thousand to nearly 10 million geoduck seed. Sand substrate nurseries may lend themselves to the successful and cost-efficient culture through the juvenile phase of other molluscs and are especially applicable where labor is at a premium.

Beattie, J. H.; Blake, B., and Herren, D. Improving survival of planted juveniles of the geoduck clam (*Panopea abrupta*) using predator exclusion devices. TRIENNIAL-MEETING-OF-FISH-CULTURE-SECTION-OF-AMERICAN-FISHERIES-SOCIETY-WORLD-AQUACULTURE-SOCIETY-NATION-SHELLFISHERIES-ASSOCIATION. 1995; 14(1):260. CODEN: Aquaculture 95', San Diego, California (USA), 1-4 Feb 1995; ISSN: ISSN 0077-5711. Abstract: Washington Department of Fish and Wildlife (Formerly Washington Department of Fisheries) personnel have been culturing the geoduck clam since the 1970s. Staff at the Point Whitney Laboratory developed techniques for larval and juvenile culture. During the 1980s the scale of culture expanded to the production of millions of 10 mm seed geoduck per year. The seed were planted into subtidal areas by broadcasting them from the stern of a slowly moving boat. Upon reaching the substrate most of the juvenile geoducks dug in successfully without being preyed upon. Two years after these broadcast plants, dive surveys for young clams revealed few had survived. In almost every case the survival estimate was less than 1 percent. In searching for a cause for this poor survival, Point Whitney biologists performed predator experiments. The most striking results of these experiments revealed that during a 48 hour exposure period, crabs (*Cancer productus* and *Cancer gracilis*) would consume 30 to 40% of all sizes of geoduck seed tested. In testing various methods of protecting the seed from predators, hatchery personnel found an effective deterrent to predation: vertically installed PVC pipe. In 1991 on 4 State Park beaches, one foot long sections of 4-inch and 6-inch diameter PVC pipe provided protection for the geoduck seed. Average survival from these intertidal plants varied from 20 to 70% ten months after planting. Another type of protective device tested in subtidal areas was paper composite tree planting cones. These cones also proved to be effective in protecting the geoduck juveniles from predation. Recovery of geoducks planted in cones averaged 20% while recovery of geoducks planted without protection was 0%. (DBO)

Bower, S. M. and Blackbourn, J. (Department of Fisheries and Oceans, Pacific Biological Station). Geoduck clam (*Panopea abrupta*): Anatomy, Histology, Development, Pathology, Parasites and Symbionts: Introduction.; 2003.

--- (Department of Fisheries and Oceans, Pacific Biological Station). Geoduck clam (*Panopea abrupta*): Anatomy, Histology, Development, Pathology, Parasites and Symbionts: Lesions of unknown cause on geoduck clams.; 2003.

Boyle, Brian and Wilkerson, William R. (Washington State Department of Natural

Resources and Washington State Department of Fisheries). The Puget Sound Commercial Geoduck Fishery - Management Plan; 1985.

Bradbury, A. Survival of hatchery-grown geoduck (*Panope abrupta*) seed in Puget Sound, Washington. J.-SHELLFISH-RES. 1989. Vol. 8, No. 1, P. 318. 1989. CODEN: 42. Annu. Meet. Pacific Coast Oyster Growers Assoc. and Natl. Shellfish. Assoc. Pacific Coast Sect., Olympia, WA (USA), 22 Sep 1988; ISSN: ISSN 0077-5711. Abstract: Washington Department of Fisheries has been experimentally seeding subtidal tracts in Puget Sound with juvenile geoducks (*Panope abrupta*) since 1976, to augment the naturally low recruitment rate of geoducks so that such tracts may be commercially exploited on a more frequent basis. Since 1985, 13.7 million hatchery-grown juveniles between 2 and 22 mm shell length have been seeded subtidally either by divers or by an apparatus which scatters the seed on the surface. Follow-up survival estimates are made via dredge samples or diver counts and have ranged from 0%-10.7% after 2 years. A survival rate of 5% would make the program cost-efficient. Survival appears highest in tracts relatively free of predators such as flatfish, shrimp, snails, and starfish. Long-term predation appears lowest in mud/sand substrates rather than pure sand. Other variables apparently affecting survival include seed size (10 mm), seed density (30 seed/m super(2)), season (late spring.early summer), and proximity to adult geoducks.

Bradbury, A.; Sizemore, Bob; Rothaus, Don, and MacGregor, Leslie (Washington Department of Fish and Wildlife). Stock Assessment of Geoduck Clams (*Panopea abrupta*) in Washington.

Bradbury, A. and Tagart, J. V. (Washington Department of Fish and Wildlife). Modeling Geoduck, *Panopea abrupta* (Conrad, 1849) Population Dynamics. II. Natural Mortality and Equilibrium Yield. Journal of Shellfish Research. 2000; 1963-70.

Breen, P. A., Gabriel, C., and T. Tyson. 1991. Preliminary estimates of age, mortality, growth, and reproduction in the hiatellid clam *Panopea zelandica* in New Zealand. New Zealand Journal of Marine and Freshwater Research. 25(3): 231-237. Life history parameters were evaluated for *Panopea zelandica*, the larger and more widely distributed *Panopea* species in New Zealand. No ecological studies had been performed on this species at the time of publication. *P. zelandica* was found to occupy sand and mud habitats at a water depth of 10-25 m. *P. zelandica* was determined to be shorter lived and smaller than the Pacific coast relative, *P. abrupta*. Mean commercial length for *P. zelandica* was 110.08 ± 12.7 mm, ranging from 61-145 mm, compared to 150 mm for *P. abrupta*. Mean weight was 298.4 ± 5.16 g ranging from 73-491 g. *P. zelandica* lived on average 12-13 years with a maximum life span of 34 years, compared to 28-61 years for *P. abrupta*. Growth rates appeared similar for both species with the most rapid growth occurring in the first 10 years. Gonadal development analysis suggests that spawning occurs in summer. Natural mortality was .20 for individuals 10 years or older. According to sustainable yield models, a higher percentage of annual harvestable virgin biomass would be permissible for *P. zelandica* compared with *P. abrupta*.

Breen, P. A.; Shields, T. L., and Department of Fisheries and Ocean, Nanaimo B. C. Canada. Age and size structure in five populations of geoduck clams (*Panope generosa*) in British Columbia. CAN.-TECH.-REP.-FISH.-AQUAT.-SCI. 1983. No. 1169, 66 Pp. 1983. Abstract: Geoduck clams (*Panope generosa*) were counted and sampled at five British Columbia sites. Samples were aged by counting growth rings on acetate peels made from shell sections. Mortality rates were estimated from age frequencies, and found to be in the range M = 0.01-0.02. These estimates and those of growth rate are similar to those seen in Washington State populations. The effect of harvesting on sediment structure and meiofaunal community composition was also examined. Harvesting has no effect on sediment structure, and had only small effects on the meiofauna. Diversity apparently increased as a result of harvesting. Density estimates showed that the fishery can reduce geoduck density to low levels. The distribution of geoducks within plots was uniform at both harvested and unharvested sites. The authors describe a method of counting geoducks that may result in more accurate estimates in future surveys.

Burger, L.; Rome, E.; Campbell, A.; Harbo, R.; Thuringer, P.; Wasilewski, J., and Stewart, D. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Analysis of landed weight information for geoduck clams (*Panopea abrupta*) in British Columbia, 1981-1995. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1995-Part-1-Bivalves Waddell,-B.J.-(Eds); Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.) . 1998; (2217):363-374. Abstract: Average weight data for geoducks, Panopea abrupta, taken from 68 landings, is presented for the three geoduck management areas in British Columbia (North Coast, west coast of Vancouver Island (WCVI) and the inside waters of Vancouver Island (Inside Waters)), between 1981 and 1995. The average weight of intact landed geoducks was 1315.11 g for the North Coast, 1136.44 g for the WCVI and 996.69 g for the Inside Waters. Average weights for specific locations within the 3 management areas are presented. A database has been created to accommodate future weight information. Future sampling should collect weight information from index sites (i.e., locations already sampled) to provide information regarding the impact of protracted harvesting on local populations. Market samples will also be collected from harvest areas not previously sampled to expand the existing coastwise database of average weight information. Geographic coordinates of harvest locations must be recorded in the future to allow for more accurate comparisons of average weights of samples taken from the same harvest site over time.

Caffey, A.; Blake, B., and Cooke, W. Enhancement efforts on state tidelands by the WDFW intertidal shellfish enhancement project. Journal-of-Shellfish-Research [J-Shellfish-Res] 2001 Vol. 2001; 20(3):1195 . CODEN: 54. Annual Meeting of the National Shellfisheries Association Pacific Coast Section and Pacific Coast Shellfish Growers Association, Warm Springs, OR (USA), 27-29 Sep 2000;

ISSN: ISSN 0730-8000. Abstract: Due to an increasing demand for clam and oyster resources on public tidelands in Washington, the Washington Department of Fish and Wildlife (WDFW) developed the Intertidal Shellfish Enhancement Project in 1988. The goal of this project is to increase recreational opportunities by way of planting clam and oyster seed, as well as harvestable size oysters, onto public tidelands. Species targeted in the past have been Pacific oysters, geoduck and Manila clams. In the last few years, research has been conducted on culturing and enhancing native species such as butter, native littleneck clams and cockles. Enhancement efforts occur throughout Puget Sound. Creel surveys and population assessments of targeted clam species are conducted each year by WDFW and tribal staff. This information is passed to the Intertidal Enhancement Project and beaches are seeded according to Intertidal Management plans and needs. The Enhancement Project purchases Pacific oyster seed and harvestable size oysters to be planted by commercial growers as directed by WDFW staff. The Point Whitney Shellfish Hatchery provides geoduck and Manila clam seed. Research performed by the WDFW Shellfish Hatchery on native species of clams such as butter, littleneck clams and cockles, have provided the Enhancement Project with small groups of seed for test plots, which will, in turn, lead to large scale planting of native species in the future.

Cain, Therese Armetta (Washington State Department of Fish and Wildlife). The Effects of Geoduck Fishing on *Cancer magister* and *Cancer productus* in Hood Canal, Washington. Brinnon, Washington; 1995; Appendix 2.

Campbell, A.; Clapp, B.; Hand, C. M.; Harbo, R.; Hobbs, K.; Hume, J., and Scarf, G. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Survey of geoduck population density in Goletas Channel, 1994. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1995-Part-1-Bivalves Waddell,-B.J.-(Eds); Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.) . 1998; (2214):319-344. Abstract: A survey was conducted in five areas on the northern side of Vancouver Island along the southeast end of Goletas Channel, which were considered to have been extensively harvested from 1984-1989, during 13-21 September, 1994, to estimate the density of geoducks (*Panopea abrupta*). The paper uses the survey results with catch data from harvest logbooks to estimate harvest rates and original biomasss of geoducks prior to the fishery. The two main objectives of the present paper were to determine: 1) the current status of the geoduck abundance, by estimating the bed area, densities and biomass of geoducks using dive surveys during September 1994; and 2) the original geoduck fishable biomass prior to the opening of the fishery in 1984 in the 5 survey areas. Geoduck biomass estimated in the aeas of this survey were higher than those previously estimated from harvest logbooks for quota estimation. The main reason for this was the low area estimate of geoduck bearing beds (64 ha) recorded in the logbooks. The small bed locations indicated by the fishers were probably due to either high geoduck abundance or density in patchy areas where the fishers remained for most of their harvesting without recording the extent of the beds.

Campbell, A.; Hand, C. M.; Paltiel, C.; Rajwani, K. N., and Schwarz, C. J. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Evaluation of some survey methods for geoducks. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1996 Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.) . 1998; (2221):5-42. Abstract: Four survey methods to estimate geoduck, (*Panopea abrupta*) density and biomass with the appropriate parametric and bootstrap analytical techniques are described. For all survey types, the primary sampling unit is a transect (or cluster of secondary sampling units of 10 m super(2) quadrats), the placement of which depends on the survey type: 1) systematic, 2) two-stage grid 3) three-stage or 4) two-stage. Example data sets analysed for survey types 1, 3 and 43 provide similar density estimates. However survey types 3 and 4 are more efficient in terms of area covered per time period than survey 1. Optimizing sampling design for a two-stage survey was also examined. Survey type 4, with randomly placed transects and sampling every second or third quadrat, is logistically easier to implement for field crew than survey type 1 or 3.

Campbell, A. and Rajwani, K. N. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Optimal sample sizes for geoduck biosamples. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1996 Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.). 1998; (2221):43-69. Abstract: Sampling for mean weight, mean age or age structure of geoduck, (*Panopea abrupta*) populations during field surveys was considered as a three-stage sampling problem. Optimum allocation of sampling resources was obtained by minimizing the variance of the variable of interest for a fixed total time cost. Example data of biosamples collected from five geoduck beds located throughout British Columbia were used in the optimizing survey design analyses. These optimal designs were found to be sensitive to costs as well as estimated variances. For each optimal design considered, the amount of time (cost) to process a geoduck for age was greater than for a weight measurement. More geoducks were required for mean age compared to mean weight estimates because of the higher variability in ages compared to weights of geoduck. The most reasonable sample requirement depended on the objective variable to measure and the amount of time required for obtaining the samples. For mean weights about 20 geoducks per site within a bed with 1 site per bed from 3 to 4 beds could be sampled per survey day. For both mean weight and age about 60 geoducks per site within a bed, with 1 site per bed from 2 to 4 beds could be sampled. For age structure analyses about 100 geoducks per site within a bed, with 2 sites per bed and 2 beds could be sampled per survey. An additional approximate 10% of geoducks should be added to the sample size due to damage to soft body parts and shell breakage during sample collection, transportation and processing.

Cheney, D. P. and Pitts, J. L. Application of a shellfish science club model in Puget Sound, Washington. Journal-of-Shellfish-Research. 2000; 19(1):651. CODEN: 92. Annual Meeting of the National Shellfisheries Association, Seattle, Washington (USA), March 19-23, 2000; ISSN: ISSN 0730-8000. Abstract: The

Pacific Shellfish Institute (PSI) provided training and facility development for science and vocational teachers in schools and tribal communities throughout the greater Puget Sound region to apply a shellfish model developed for the Quilcene-Brinnon Schools Shellfish Science Club, Quilcene, Washington. The program and curriculum of this model were designed to teach high school students how to farm shellfish, maintain water quality and habitat, and utilize the scientific method in resource conservation. Winner of the President's National Environmental Education Award, the model combines community education with a "junior achievement", entrepreneurial incentive for students, using farmed shellfish at local fairs and festivals. The introduction of water quality education for K-12 students and the establishment of a working relationship with local shellfish farmers moves the classroom into the field. PSI initially extended the concept to schools and tribes through a series of workshops. Two high schools were identified with staff and facilities suitable for the program. Teachers and students were introduced to a variety of shellfish culture concepts. These included: a) classroom instruction; b) population assessments and surveys on a commercial oyster culture site; c) farm tours to view shellfish polyculture (clams, oysters, geoducks); d) shellfish hatchery and processing plant field trips; and e) geoduck farming techniques and research site sampling. PSI is continuing to work with both schools to assist them with technical information, shellfish bed management, and coordination with shellfish farmer mentors. This project was supported by a grant from the Puget Sound Water Quality Action Team, Public Involvement and Education Fund.

Chew, K. K. Status of shellfish culture in Alaska. AQUACULT.-MAG. 1987; 23(5):79-87; ISSN: ISSN 0199-1388. Abstract: There are several species, I know, that are currently being cultured or are candidates for aquaculture in Alaska. Currently, the Pacific oysters (*Crassostrea gigas*) is the most cultured species followed by a small production of mussels (*Mytilus edulis trosselus*). Intensive research and development are underway for native little neck clams (*Venerupis staminea*), butter clams (*Saxodomus giganteous*), and rock scallop (*Crassadoma gigantea*). Interest in geoducks (*Panope abrupta*) aquaculture is beginning. The future prospects and present status of each of these species will be discussed very briefly based upon information provided by the state of Alaska and Mr. RaLonde.

---. Update on geoduck clam culture in the Pacific Northwest. Aquacult.-Mag. 1998; 24(1):79-82; ISSN: ISSN 0199-1388. Abstract: The continuing upsurge of interest in geoduck (*Panopea abrupta*) culture brings me back to this subject for an update. Being the largest clam in North America, geoduck status has switched from that of mainly a novelty clam for recreation fisheries to what is now one of the most expensive clams in the commercial market in terms of live weight value. This clam is able to grow over one hundred years and can reach upwards to 8.5-9.0 pounds. Geoduck is not considered the best looking clam. Nonetheless, it now retails at approximately $10/pound live weight. Part of the reason for this is that there is great demand for this product in many parts of Asia, including Hong Kong, Japan, and Taiwan. Please note two previous articles written in Aquaculture Magazine in reference to the geoduck clam (Nov.-Dec. 1992 issue, "Cultivation of the Geoduck, Largest Growing Clam in the United States;" May-June 1997 issue, "Washington State Molluscan Shellfish Harvest: A Mixed Bag").

Ciocco, N. F. The *Panopea* clam. A new fishery resource from the Argentinean Sea. Infopesca-Int. 2000; 6:36-39. Abstract: The *Panopea* clam or 'southern geoduck' (*Panopea abbreviata*) is among the non-traditional fishery resources that need to be investigated and explored. This is a bivalve for which neither biological or ecological background knowledge exists in South America. In order to cover such missing information, the author of the article is currently conducting an investigation project financed by CONICET (Argentina). This article presents the preliminary results.

Clapp, B. Underwater harvester's association geoduck enhancement program. Journal-of-Shellfish-Research. 2000; 19(1):p. 620. CODEN: 92. Annual Meeting of the National Shellfisheries Association, Seattle, Washington (USA), March 19-23, 2000. Abstract: The Underwater Harvester's Association (UHA) is comprised of all the licensed geoduck and horseclam fishermen in British Columbia (BC). The geoduck fishery started in BC in 1976, the UHA was formed in 1981 and in 1989 the fishery changed to an Individual Vessel Quota (IVQ) system, which was initiated by the UHA. From 1989 to 1998 the UHA saw a continual reduction in their annual quota. The reduction in quota was a result of changes in the knowledge of bed areas and geoduck density estimates. In 1994 the UHA funded and initiated an enhancement program to plant hatchery raised juvenile geoducks in existing beds to enhance the local populations. The initial objectives for the program were to explore the feasibility of geoduck enhancement, to increase stock for brood and eventually to offset harvest (partially). This was the first shellfish fishery to try enhancement in BC. There were no hatchery facilities in BC and no planting technology available for the UHA to copy. In 1999, there was a successful geoduck hatchery and the UHA has a machine that can plant up to 50,000 juvenile geoducks per day. The details of how this enhancement program would be incorporated into the wild geoduck management plans have not been explored.

Cole, L. R.; Beattie, J. H., and Chew, K. K. Optimal substrate strategy for survival and growth of early juvenile geoducks, *Panope abrupta* in a sand nursery. J.-SHELLFISH-RES. 1989. Vol. 8, No. 2, Pp. 411-412. 1989. CODEN: 43. Annu. Meet. of the Pacific Coast Oyster Growers' Assoc. and Natl. Shellfisheries Assoc. (Pacific Coast Section), Seattle, WA (USA), 21-23 Sep 1989; ISSN: ISSN 0077-5711. Abstract: Present techniques at the State Shellfish hatchery at Pt. Whitney place newly metamorphosed *Panope abrupta* in 20' x 12' sand raceways, which have increased survival and growth dramatically over the original upwell system. But survival from metamorphosis to 8 mm seed is still only about 7%, and growth and health are extremely variable. Hatchery observation and recent work at the University of Victoria indicate that early juveniles are mobile, with a well-developed foot, and remain in the upper centimeter of substrate for at least one month post metamorphosis. Juveniles are capable of using byssal threads to attach to the substrate or each other until well after they become sedentary at 5-6 mm. A study during the summer of 1989 tested 3 substrate variables and their interactions to determine optimal substrate strategy for juveniles less than or approximate to 2 mm shell length at the Pt. Whitney nursery. The variables include: 1) grain size; 2) substrate depth and 3) bottom surface. It is expected to increase survival and growth in the nursery, to reduce costs through conservative use of sand, and to find clues to preferred recruitment substrate in the wild.

Cole, L. R.; Beattie, J. H.; Chew, K. K., and Washington Univ., Seattle USA Sea Grant Program. Geoducks (*Panope abrupta*) in a sand substrate nursery. [Nosho,-T.Y.;Chew,-K.K.-eds.]. REMOTE-SETTING-AND-NURSERY-CULTURE-FOR-SHELLFISH-GROWERS:-WORKSHOP-RECORD. 1991; 55-56. CODEN: Remote Setting and Nursery Culture for Shellfish Growers: Workshop, Olympia, WA (USA), 19 Feb 1991; ISSN: ISBN 0-934539-15-4. Abstract: The geoduck (*Panope abrupta*) industry in Washington State harvests about five million pounds a year from Puget Sound. Given inconsistent survival and growth of the juveniles in the nursery system, experiments during 1989 and 1990 tested modifications of the nursery environment in nursery microcosms. Sand grain size, planting density, site effects, and food sources were tested for effects on postlarval geoduck survival and growth. Dried *Tetraselmis suecica* was added either in a slurry to the substrate or suspended gradually in the water column, and compared with treatments of suspended cultured algae (*Chaetoceros muelleri*) and unfed controls. Preliminary results show significant differences in growth between treatments with food available to the substrate and those with food added only to the water column.

Cole, Lauran Ruth. Growing juvenile geoducks (*Panope abrupta*) in a Sand Nursery: Studies in Stocking Density, Substrate Type and food Availability. [MS Thesis]. Seattle, WA: University of Washington; 199150 pp.

Cooper, K.; Olsen, S.; Bancroft, R. W.; Hovis, B., and Shriner, J. Large-scale hatchery and nursery rearing of the Pacific geoduck clam *Panopea generosa* (Gould). J.-SHELLFISH-RES. 1985. Vol. 5, No. 1, P. 50. 1985. CODEN: Annu. Meet. National Shellfisheries Association, West Coast Section, Bellingham, WA (USA), 7 Sep 1984. Abstract: A pilot hatchery and nursery has been built at the Point Whitney Shellfish Lab to rear Pacific geoduck clams (*Panope generosa*). Techniques developed in the pilot stage will be applied to produce 30 x 10 super(6) juvenile clams (10-15 mm in length) per year. The juvenile clams will be planted in areas where marketable clams have been harvested by commercial divers. Hatchery and nursery techniques are described. In experiments, competent larvae were induced to undergo metamorphosis within 12 hours by exposure to tubes of the polychaetes *Spiochaetopterus costarum*, *Diopatra ornata*, *Phyllochaetopterus prolifica*), the supernatant and precipitate from a seawater homogenate of tubes of *S. costarum* , and a 10 super(-5) M solution of the amino acid L-Dopa. Analysis of variance showed no significant differences in the response of larvae to the above treatments.

Cooper, Ken and Pease, Bruce (Coast Oyster Company and Washington Department of

Fisheries). Induction of Settlement and Metamorphosis of the Geoduck Clam, *Panope abrupta* (Conrad), by Polychaete Tubes with Implications for Recruitment and Adult Distribution Patterns.

Cox, R. K. The geoduck clam fishery in British Columbia, Canada. J.-SHELLFISH-RES. 1981. Vol. 1, No. 1, P. 111. 1981. CODEN: Annu. Meet. of the National Shellfisheries Association, Hyannis, MA (USA), 9 Jun 1980. Abstract: Harvesting of subtidal stocks of the geoduck clam, *Panope generosa* (Gould), in British Columbia, Canada began in the fall of 1976. Less than 43.4 metric tons were landed that year from areas in the Gulf of Georgia. By 1979, landings increased to 2,405 metric tons, and main fishing effort was focused on the western coast of Vancouver Island in Clayoquot and Barclay sounds. Indications for 1980 are that the fishery will continue to expand into northern coastal regions with landing approaching 3,000 metric tons. A quota of 3,630 metric tons has been set for the fishery. Surveys to date indicate standing stocks in excess of 80,000 metric tons. Many coastal areas remain to be surveyed. The fishery is restricted to diver-harvesters who dig each clam individually using a high-pressure water jet. Present harvesting occurs between the 10- to 60-foot level. Average weight of adult geoducks in British Columbia is 1.1 kilos, and under good conditions a single diver can harvest 350 kilos per day.

Curtis, K. M. PSP in geoducks: Variability, anatomical distribution, and comparison of two toxicity testing methods. Journal-of-Shellfish-Research. 1998; 17(4). Abstract: The purposes of this study were to: (1) determine variability in paralytic shellfish poisoning (PSP) toxicity in the geoduck clam (*Panope abrupta*), i.e., within a single population, between various sets of populations, and seasonally; (2) determine anatomical distribution of PSP toxins; and (3) compare two PSP testing methods: From summer through winter 1997, 15-20 geoducks were collected biweekly from a shallow and a deep location in each of two tracts in Puget Sound, Washington: Agate Pass (AP) and Quartermaster Harbor (QH). Geoducks were dissected into siphon, mantle, and visceral portions. All portions were assayed separately using the mouse bioassay (MBA), while only the visceral portions were assayed using the receptor binding assay (RBA). Results indicated that individual variability was high in the shallow areas with coefficients of variation (CV) ranging from 20-98%, and lower in the deep areas (CV = 18-62%). Seasonally, variability did not change in either of the QH areas and increased in both of the AP areas. Only shallow geoducks were toxic in QH. All geoducks were toxic in AP, with the shallow ones significantly more toxic 18% of the time. Anatomically, PSP toxins were isolated to the visceral ball in all geoducks throughout the study period. There was a highly significant positive correlation between the MBA and RBA, with the RBA slightly overestimating the MBA at lower toxicity levels. Variability information will aid fishery managers in maximizing utilization of the resource, while at the same time protecting public health from the dangers of PSP.

Curtis, K. M. and Chew, K. Comparison of two PSP testing methods, anatomical distribution and individual variability in PSP toxins in the geoduck clam. Journal-of-Shellfish-Research. 1998; 17(1):322-323. CODEN: Aquaculture '98, Las Vegas, Nevada (USA), 15-19 Feb 1998. Abstract: Paralytic Shellfish Poisoning (PSP) has a long history of causing major problems for shellfish consumers all over the world. Serious illness or death can occur. Recalls of toxic shellfish can be damaging to everyone as well. Recalls may reduce consumer confidence in the shellfish product, and ultimately lead to devaluation of the product and loss of income to harvesters, producers and sellers. Fortunately, many areas of the world are setting up monitoring programs to minimize the threat of PSP poisoning to consumers, and also to help minimize product recall. In Washington state, the geoduck clam, *Panope abrupta*, is a valuable economic resource, where it is harvested and sold as a food product. However, the clam bioaccumulates the toxic dinoflagellate, *Alexandrium catenella*, an organism responsible for PSP. This may devalue the geoduck as a food item for human consumption. Historically, levels of PSP toxins in the tissues of the geoduck were not considered a problem; it was assumed that the gut was thrown out and the rest consumed. In addition, harvesting occurred in areas of Puget Sound where there were no problems with PSP. Now, it has been learned that various Asian and Tribal communities are actually consuming the gut and new tracts are being surveyed and opened for harvest in these traditional 'hot' areas. The current method in Washington State for monitoring of PSP in geoduck may not be valid, especially as new tracts in 'hot' areas are being opened. A composite sample of three geoducks from each of two tracts in Puget Sound are tested for toxicity, approximately once a week. When PSP levels exceed the regulatory level of 80 mu g/100g in this composite sample, the fishery is closed and remains closed until PSP levels have dropped below 80 mu g. This method does not account for variability in the clams, and may lead to late closures or premature openings of the fishery. No information is currently available regarding the relationship between PSP toxins and the geoduck. The purpose of this study is to address the following questions: (1) What is the variance in toxicity between individual geoducks, and does it correlate with season, depth, substrate or harvest site; (2) what is the anatomical distribution of PSP toxins in the geoduck; and (3) how does the receptor-binding assay compare to the mouse bioassay in testing for PSP? From July through December, 1997, geoducks were collected weekly from two tracts within Puget Sound which were known to have had problems with PSP. Two sites within each tract were chosen at random, and all subsequent sampling took place at those sites. Data collected at each site included: date, time of collection, depth, substrate, length, weight, and quality of geoduck. Neck, body, and visceral ball were analyzed separately using the mouse bioassay, with the same samples analyzed via the receptor-binding assay. Results were analyzed using simple statistical methods in order to address the previous questions, and will be discussed. New information regarding variability in the geoducks may lead to a revision of the current monitoring program for PSP in geoducks. This information may also minimize product recall, as well as minimize the possible loss of thousands of dollars for state and tribal harvesters.

Curtis, K. M.; Trainer, V. L., and Shumway, S. E. Paralytic shellfish toxins in geoduck clams (*Panope abrupta*): Variability, anatomical distribution, and comparison of two toxin detection methods. Journal-of-Shellfish-Research [J-Shellfish-Res]. 2000; 19(1):313-319; ISSN: ISSN 0730-8000. Abstract: The geoduck clam, *Panope abrupta*, is a valuable economic resource in Washington State. Prior to the mid 1970s, the levels of paralytic shellfish poisoning (PSP) toxins in Washington State geoducks were not considered by the Washington State Department of Health (WDOH) to be a risk to public health because the viscera were presumed to be discarded. Recent monitoring information indicates that geoducks accumulate high levels of toxins, primarily in the viscera. The purposes of this study were to determine: (1) the seasonal concentration of paralytic shellfish toxins in geoduck clams at two sites and at two depths within each site; (2) the variability of PSP toxin levels among individual clams within each site; (3) the anatomical distribution of toxins: and (4) the correlation between two methods for estimating PSP toxins. From the summer of 1997 through the winter of 1998, 12-24 geoducks were collected biweekly from a shallow (7 m) and a deep (17 m) location in each of two tracts in Puget Sound, Washington: Quartermaster Harbor (QH) and Agate Pass (AP). Geoducks, dissected into siphon, mantle, and visceral portions, were assayed separately using the mouse bioassay (MBA), while only the visceral portions were assayed using the receptor-binding assay (RBA). Results indicated that toxin variability between individual clams was high in the shallow areas, with coefficients of variation (CVs) ranging from 20-98%, and lower in the deep areas (CV = 18-62%). In QH, only geoducks from the shallow water had toxin levels greater than the regulatory level of 80 mu g saxitoxinequivalents (STX eq) times 100 g shellfish tissue super(-1), while all geoducks from AP contained toxin above the regulatory level, with clams from shallow water considerably more toxic than those from deep water. Anatomically, the highest concentrations of PSP toxins were localized in the viscera of geoducks. There was a significant positive correlation between toxin levels measured by the MBA compared to values obtained using the RBA (r super(2) = 0.83). The large differences in toxicity between geoducks sampled at different depths and harvest tracts indicate that careful management plans must be designed in order to ensure public health.

Curtis, Kelly. Toxicity of Paralytic Shellfish Poisoning (PSP) in the Geoduck clam. University of Washington, School of Fisheries.

Curtis, Kelly M. Paralytic Shellfish Toxins in Geoducks Clams (*Panope abrupta*): Variability, Anatomical Distribution, and Comparison of Two Toxicity Testing Methods. Masters Thesis, University of Washington. 1999.

Dahman, D. Planting experiment at Dahman's shellfish co. Clam-and-Oyster-Farming Nosho,-T.-(Ed.) Washington-Univ,-Seattle-USA-Sea-Grant-Program 1998 P. 57. 1998; p. 57. CODEN: 7. Conf. for Shellfish Growers: Clam and Oyster Farming, Olympia, WA (USA), 3-4 Mar 1997. Abstract: Last summer, our company planted 11,000 geoduck seed clams. We punched holes in the sand with a steel rod and dropped one clam into each hole. The density was one animal per square foot. It sounds simple enough, but it took nine of us two days to complete the plant. The only immediate problem observed in the area was moon snails. We

haven't had a chance to assess the outcome yet, but it looks promising from casual observations. We bought broodstock to condition, spawn and produce larvae. This experience taught us the following: Collecting enough females is a major problem. We bought a total of 200 animals for broodstock and found that only 11 were females. Geoducks are dribble spawners. Larval rearing and setting are currently inconsistent. Feeding larvae the proper amount of food is critical. If you over-feed the larvae, they will die. Keep algae cell densities on the low side. Geoduck necks don't always "show" on the grounds during February and March. Apparently, many of the geoducks retract their necks during this period and will not "show" again until April or May. The time period seems to depend on the area. Geoduck culture provides an opportunity for existing shellfish farms to expand and diversify operations. Geoduck culture also allows the use of marginal areas unsuitable for farming oysters and clams. However, growers must be patient and consider that it will take four to five years to produce a crop.

Davis, J. Bivalve aquaculture in the pacific northwest: Current farming methods and research activities [SC:All]. Abstracts-of-the-First-Annual-Northeast-Aquaculture-Conference-and-Exposition Barber,-B.-(Ed.) . 1998; 22. CODEN: Northeast Aquaculture Conf. & Expo., Rockport, Maine (USA), 18-19 Nov 1998. Abstract: Bivalve aquaculture in the Pacific Northwest is focused on a variety of species which take into account the variety of habitats found there, and the economics of rearing bivalves in relatively cool and productive northeast Pacific waters. A dichotomy of farming methods exists with suspended mussel and oyster culture making up only a small percentage of the farmed product, as intertidal clam and oyster culture dominate the focus of activity. Specifically, hatchery reared Mediterranean mussels (*Mytilus galloprovincialis*), Pacific oysters (*Crassostrea gigas*) and European flat oysters (*Ostrea edulis*) are currently reared using standard suspended culture methods from rafts and surface long lines. Intertidal oyster culture is dominated by Pacific oysters, although Kumomoto oyster (*C. sikamea*) culture is practiced where intertidal conditions are suitable. On-bottom culture, intertidal longline, on-bottom longline and rack and bag culture are all current methods in use. Intertidal clam culture is focused on the Manila clam (*Tapes philippinarum*) and the geoduck clam (*Panope abrupta*). Manila clam culture is focused on harvesting clams originating from sets produced from naturalized populations and enhancement of beaches with gravel and other substrates using hatchery reared seed. Geoduck culture is rapidly evolving and utilizes intensive, high density culture practices and hatchery reared seed, exclusively. Finally, scallop culture (*Patinopectin caurinus*, *P. yessoensis*, and *Crassodoma giganteus*) are in their infancy with respect to the rest of the shellfish industry and are currently limited by bottlenecks in hatchery production.

Davis, J. P.; Barenburg, C., and Pederson, D. Burrowing response of juvenile geoducks (*Panopea abrupta*) to changes in temperature and salinity. Journal-of-Shellfish-Research. 2000; 19(1):689. CODEN: 53. Ann. Meeting of the Pacific Coast Oyster Growers Assoc. & Natl. Shellfisheries Assoc., Vancouver, WA (USA), Sept. 29-Oct. 1, 1999; ISSN: ISSN 0730-8000. Abstract: Geoduck clams, *Panopea abrupta*, are a newly cultured species and the development of geoduck culture techniques, coupled with out planting methods have not been perfected. Environmental parameters likely have a significant effect on the burrowing behavior of clams which in turn may greatly influence the level of survivorship of newly planted seed. The burrowing behavior of three size classes of juvenile geoduck clams was measured in response to exposure to a suite of temperature and salinity conditions. Seed were exposed to all combinations of six temperature (8, 11, 14, 17, 20, & 23 degree C) and six salinity (20, 22, 24, 26, 28, & 30 ppt) treatments. Three different seed classes were tested; small (4.6 mm mean shell length), medium (7.2 mm) and large (9.5 mm) geoducks. All clams were maintained under common conditions prior to testing burrowing response. Results indicate that all seed size classes showed maximal burrowing response at median temperatures (11, 14, and 17 degree C) and higher salinities (26, 28, and 30 ppt). The response for all size classes indicated a proportionate increase in burrowing rate as conditions neared ambient salinity (30-32 ppt). Size was also a significant factor as large and medium seed demonstrated high burrowing response only between 11 and 14 degree C and at higher salinities, and reduced burrowing response at low (8 and 11 degree C) and high (23 degree C) treatment temperatures. The burrowing response of small seed in all treatments was uniformly higher compared to medium and large seed across all temperature and salinity treatments; however as also seen for large and medium sized cohorts, burrowing behavior at salinities less than 26 ppt. was greatly reduced. Avoiding extremes in temperature and in particular salinities less than 26 ppt, even for short periods of time, may significantly increase overall planting success for culture operations.

Elston, R.; Gee, A., and Herwig, R. P. Bacterial pathogens, diseases and their control in bivalve seed culture. Journal-of-Shellfish-Research. 2000; 19(1):644. CODEN: 92. Annual Meeting of the National Shellfisheries Association, Seattle, Washington (USA), March 19-23, 2000; ISSN: ISSN 0730-8000. Abstract: Vibriosis is known as a disease of intensively cultured larval shellfish but bacterial pathogens cause significant losses in nursery cultures of juvenile bivalves. Typically, rod-shaped bacteria attach to externally oriented periostracum and subsequently invade juveniles through the valve closure and along the internal shell surface. Contact necrosis and sloughing of mantle epithelium results and, when bacteria have invaded sufficiently far along the mantle, they invade the still patent coelomic cavity of juvenile bivalves. A chronic form of the disease occurs less frequently. Detailed studies of invasive juvenile bacterial diseases are underway for the Pacific oyster (*Crassostrea gigas*), Kumomoto oyster (*Crassostrea sikamea*), geoduck clam (*Panope abrupta*), and other species. *Vibrio tubiashi*, *V. anguilllarum*, *V. tapetis* and *V. splendidus* have previously been reported as causative or associated with larval bivalve mortalities but there also appear to be significant unnamed vibrio-like pathogens of bivalve juveniles. Results of current studies to characterize pathogenesis and link disease types to bacterial species are underway, including identifying characteristics of the causative agents by morphological, physiological, nucleic acid and fatty acid analysis. Bacterial pathogens enter culture systems via sea water, brood stock transport of in algal food cultures. They can be maintained on system surfaces and their growth augmented by dissolved organic substrates generated by algal cultures, external algal blooms, or metabolism of the cultured juveniles. Prevention and control strategies must include routine sanitation of system surfaces, water filtration, brood stock sanitation and maintenance of low dissolved organic levels. Antibiotics have been used in experimental settings but are not routinely used on production scale systems due to cost as well as risk of producing resistant strains. In the United States, there are no antibiotics licensed for general use on molluscan shellfish. A program to select and test probiotic strains of bacteria, as an alternative to antibiotic use, is underway and results to date will be presented.

Elston, R.; Heidel, J.; Davis, J., and Cheney, D. Intensive bivalve health management. Journal-of-Shellfish-Research. 1998; 17(4). CODEN: 52. Annual Meeting: Pacific Coast Oyster Growers Association and National Shellfisheries Association, Nanaimo, BC (Canada), 14-16 Oct 1998. Abstract: Growout of edible shellfish is practiced on a more or less extensive basis, but intensive hatchery production is now an essential part of culture. Intensification brings new challenges for health and disease management including a variety of highly opportunistic and aggressive infectious agents as well as nutritional and genetic diseases, and toxic conditions. Infectious diseases that have emerged in intensive hatchery and nursery operations include velar virus disease, herpes virus disease, vibriosis, hinge ligament disease, acute and chronic extapallial bacterial infections, bacterial mat disease, ameboflagellate disease and invasive ciliate disease. A recent example are bacterial mats resulting in debilitating infections of juvenile geoducks, *Panope abrupta*. These infections are initiated by Cytophaga-like bacteria that colonize the external shell surface and subsequently invade the mantle of juvenile clams, necrotizing the entire mantle. The bacterial mats may interact with the texture of composition of juvenile geoduck shells since this condition has not been observed in any other species. These conditions can be managed and ameliorated using principles of responsive health management. In many cases, there is a great deal of information lacking that is needed to fully accomplish the goal of maintaining healthy cultures of shellfish in the hatchery, nursery and in grow out areas. Sanitation and health management are two distinct objectives of intensive bivalve high health program that will discussed. Both objectives should be met by identifying standards, monitoring and responding to deviations in sanitary or health and condition standards. Supported in part by NMFS Saltonstall Kennedy Program and USDA Small Business Innovative Research Program.

Elston, R. A. and Cheney, D. Shellfish health management for enhancement, restoration and culture on the West Coast. Journal-of-Shellfish-Research. 1998; 17(4). CODEN: International Conference on Shellfish Restoration Hilton Head Island, South Carolina (USA); ISSN: ISSN 0730-8000. Abstract: Pacific and kumamoto oysters (*Crassostrea gigas* and *C. sikamea*) and manila clams (*T. philippinarum*) are widely cultured on the west coast of North America. Native bivalve culture is relatively limited by several species such as the geoduck clam (*Panope abrupta*) and native littleneck clam (*Protothaca staminea*) are part of an emerging

technology that supplies seed and adult shellfish for enhancement, restoration, and commercial production. It is essential that health management procedures be in place to prevent the dissemination of infectious diseases during these activities and to reduce operational costs. Studies on cultured seed stock in Washington, Oregon, California and Hawaii revealed opportunistic but significant bacterial pathogens and several other conditions. No diseases considered certifiable were found. A broader mortality and health study of adult oyster stocks is underway to elucidate causes of periodic mortality and establish an ongoing program of health surveillance. Developing technology for new species in culture must include health management and disease prevention in the intensive culture facilities. Morphologic pathology is the basis of disease evaluation but needs to be supplemented by microbiological and molecular methods for diagnosis and characterization of infectious diseases. Shellfish health programs for commercial producers are under development in order to better understand the disease process related to shellfish mortalities and product losses, and to foster practices that will enhance shellfish health. The health program consists of standards for brood stock management, hatchery and grow out operations, a response plan for disease outbreaks, record-keeping requirements and standards for evaluation and training.

Fisheries and Oceans, Canada (Fisheries and Oceans, Canada). 2003 Geoduck and Horse Clam Integrated Fisheries Management Plan, 21 pp.

Fyfe, David A. The Effect of Conspecific Association on Growth and Dispersion of the Geoduck Clam, *Panope generosa* [Thesis]: Simon Fraser University; 1984110 pp.

Gillespie G.E. (eds.) and Walthers, L. C. eds. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Invertebrate Working Papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1996. Can-Transl-Fish-Aquat-Sci; Traduct-Can-Sci-Halieut-Aquat . 1998; 2221344 pp. Abstract: Working Papers prepared in 1996 by Fisheries and Oceans Canada staff and reviewed by the Pacific Stock Assessment Review Committee (PSARC) are presented. These documents form the basis of biological advice given to managers for the development of fishing plans for 1997. Topics included: a framework for developing scientific advice for data-limited invertebrate fisheries; evaluation of survey methods and biological sampling requirements for geoducks (*Panopea abrupta*); quota options for the 1997 and 1998 geoduck fisheries; assessment of prawn (*Pandalus platyceros*) stocks in Statistical Area 12; assessment of inshore shrimp fisheries; studies of euphausiid populations in Jervis Inlet and Barkley Sound; quota recommendations for the 1996/97 green sea urchin (*Strongylocentrotus droebachiensis*) fisheries; and advice for management of the sea cucumber (*Parastichopus californicus*) fishery

Glude, J. B. The Clams genera *Mercenaria*, *Saxidomus*, *Protothaca*, *Tapes*, *Mya*, *Panopea*, and *Spisula*. Abstract: One of a series of reports reviewing the state of knowledge regarding selected species and analyzing their environmental requirements. The purpose of this study funded by Tennessee Valley Authority and the Electric Power Research Institute was to determine if thermal effluent or waste heat from electricity generating plants would be useful in the culture of the Pacific Salmon, the American and Pacific oysters, the clams, the marine shrimp, the freshwater prawns and the American lobster.

Goodwin, C. L. and Pease, B. (State of Washington Department of Fisheries). The Distribution of Geoduck (*Panopea abrupta*) Size, Density, and Quality in Relation to Habitat Characteristics Such as Geographic Area, Water Depth, Sediment Type, and Associated Flora and Fauna in Puget Sound, Washington. 1987; Technical Report No. 102.

---. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest). Pacific geoduck clam. BIOL.-REP.-U.S.-FISH-WILDL.-SERV. 1989; 22 pp. Abstract: The geoduck clam (*Panope abrupta* Conrad) is one of the largest burrowing clams in the world and ranges along the west coast of North American from Alaska to Baja California and along coastal Japan. It lives at depths extending from the lower intertidal zone to 110 m and is very abundant in Puget Sound, Washington, and British Columbia, where it supports important commercial fisheries. Geoduck clams are commercially fished by divers, who wash them from the substrate with hand-operated water jets. Significant portions of the catch are exported to Japan. Geoduck clams are long-lived, reaching ages of at least 146 years. Growth is rapid, but recruitment rates are low. Because of their high value, large size, and rapid early growth but low recruitment rates, they are being artificially stocked in Washington waters.

Goodwin, C. L. and Pease, B. C. (Washington department of Fisheries). Geoduck (*Panopea abrupta* (Conrad, 1849)), size, density, and quality as related to various environmental parameters in Puget Sound, Washington. Journal of Shellfish Research. 1991; 10(1):65-77.

Goodwin, C. Lynn (Wash. Dep. Fish., Brinnon, WA, USA). The assessment of subtidal geoduck clam populations by visual and photographic techniques. /[Presented at: National Shellfisheries Association Convention; 1975]. Proc.-Natl.-Shellfish.-Assoc.,-Md. 1976; 657-8. Abstract: Since 1967 the Washington State Department of Fisheries has been surveying subtidal clam stocks in Puget Sound with SCUBA divers. Geoducks (*Panope generosa*) stocks are evaluated by visual counts of siphons or siphon holes (shows). The number of geoducks detected by divers using the visual method varies considerably depending on how well the clams 'show' when the surveys are made. Preliminary observations from nine plots showed that the percentage of the true population detected in visual surveys could vary from as low as 26 to a high of 92. In more detailed studies, the percentage detected was low during the cold winter months and high during spring, summer, and fall, and averaged approximately 40% from year-around monthly samples. The percentage detected in underwater photos is also highly variable, and is subject to similar errors. The monthly 'showing factors' have been used to refine diver survey counts and the total Puget Sound subtidal geoduck population estimate. The estimate for the 33,992 acres surveyed thus far is 114,700,000 clams. Surveys with underwater TV or cameras mounted on sleds, tripods, or

other devices which come in contact with the bottom should be done with a knowledge of the effects of mechanical disturbance on the 'showing factor'. Geoducks at certain times of the year are extremely sensitive to mechanical disturbance and will withdraw their siphons from the substrate surface at the slightest contact of divers or equipment with the bottom. Geoducks have been successfully surveyed with underwater TV and large numbers of these clams have been observed in water as deep as 240 feet. Mechanical disturbance was kept to a minimum by keeping the camera and all other equipment suspended off bottom on cables. This study demonstrated that useful survey information on the populations of marine benthic organisms can be obtained with visual or photographic techniques, but the surveys should be done with knowledge of the percentage which can be detected and the effects of equipment or divers on that percentage.

Goodwin, C. Lynn (Washington State Dep. Fish., Shellfish Lab., Brinnon, WA 98320, USA). The effects of season on visual and photographic assessment of subtidal geoduck clam (*Panope generosa* Gould) populations. Veliger. 1977; 20(2):155-158. Abstract: The ability of divers to detect geoduck siphons on visual transects was found to vary greatly, depending on the season of the year. In the summer months, when the clams are actively pumping water, their siphons are easily seen by divers, but in the winter reduced pumping and retracted siphons make detection difficult. Similar changes in efficiency were noted in underwater photographs. Surveys of marine benthic organisms using direct visual counts, photographs or underwater TV should be corrected with information on the percentage of the actual population detectable.

Goodwin, C. Lynn (Washington State Department of Fisheries). Observations on Spawning and Growth of Subtidal Geoducks (*Panope generosa*, Gould). Proceedings of the National Shellfisheries Association. 1976; 6549-58. Abstract: Histological preparations of subtidal geoducks from Puget Sound were examined to determine their annual reproductive cycle. One annual spawning season occurred in spring and early summer. Most clams were in a spawned-out condition in late summer. Gametogenesis occurred rapidly in the fall and continued into the winter. By early spring, most were mature and ready to spawn. The growth rate of subtidal geoducks was estimated from marks and recovery studies in five locations throughout Puget Sound. These experiments showed that during the first 3 years of life, marked geoducks grew from 20 to 30 mm/year in total shell length. Growth of older marked geoducks was less, and the shell length in the majority over 100 mm did not increase at all. Growth rate based upon length frequency distributions from two locations amounted to about 30 mm/year for the first 3 years. This figure more accurately estimated the true growth rate because of the setback in growth caused by handling in the mark and recovery studies. Geoducks are estimated to reach the average adult size of 158 mm in 10 years and, therefore, growth is reduced. The average length of geoducks in separate populations varied from 123-.-8 mm to 171-.-3 mm in samples taken in 22 locations. The largest clam from a sample of 2037 was 206 mm. The growth rate probably varies considerably from one clam bed to another. The length-

weight curve based on 1213 pairs of observations can be expressed by the equation; log-SUB-10- weight (in grams) = -3-.-42983 + 2-.-97281 log-SUB-10- length (in millimeters). The sigmoid age-weight curve shows that the average 10-year-old geoduck weighs about 1200 grams, and the greatest annual-weight gains occur between the third and seventh years.

Goodwin, C. Lynn (State of Washington Department of Fisheries, Mangement and Research Division). Puget Sound Subtidal Geoduck Survey Data. 1978.

--- (Washington Department of Fish and Wildlife). Washington Department of Fisheries Geoduck Tract Atlas. Brinnon, Washington; 1994; Appendix 3.

Goodwin, C. Lynn and Shaul, W. (State of Washington Department of Fisheries). Age, Recruitment and Growth of the Geoduck Clam (*Panope generosa*, Gould) in Puget Sound, Washington. 1984; Progress Report No. 215.

Gribben, P. E. and Hay, B. E. Larval development of the New Zealand geoduck *Panopea zelandica* (Bivalvia: Hiatellidae). New-Zealand-Journal-of-Marine-and-Freshwater-Research [N-Z-J-Mar-Freshwat-Res] 2003 Vol. 37(2):231-239; ISSN: ISSN 0028-8330. Abstract: The larval development of the New Zealand geoduck, *Panopea zelandica*, grown under culture conditions, was described through measurements of shell morphometry using video image analysis, photomicrographs, and scanning electron microscopy (SEM). Gametes were stripped from ripe broodstock and eggs fertilised with a dilute sperm solution. Developing larvae were maintained at 17 plus or minus 1 degree C. Fertilised eggs developed into trochophores within 12 h and to D-stage larvae (105.3 mu m shell length) within 24 h. Larvae spontaneously settled after c. 16 days at c. 247 mu m shell length. Measurements of shell morphology, including total length, total height, hinge length, length of anterior end, and umbo length and height were adequate descriptors of larval development. SEM indicated that the provinculum of D-stage and developing veliger larvae lacked any teeth, although there was some development of a small lamelliform tooth on the hinge structure of newly settled post-larvae. Prominent spines common on dissoconch shells of other hiatellid clams were absent in newly settled post-larvae of *P. zelandica*. The data presented here are the first description of the larval development and larval biology of *P. zelandica*. The relative ease of spawning and rearing of *P. zelandica* suggests that the development of commercial hatchery technology for this species warrants further investigation.

Hand, C. M.; Campbell, A.; Lee, L., and Martel, G. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). A survey of geoduck stocks on North Burnaby Island, Queen Charlotte Islands, July 7-18, 1994. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1995-Part-1-Bivalves Waddell,-B.J.-(Eds); Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.). 1998; (2214):345-362. Abstract: A survey of geoduck (*Panopea abrupta*) stocks on the north end of Burnaby Island, in the lower Juan Perez

Sound management unit of the Queen Charlotte Islands (QCI), was conducted by the Haida Fisheries Program, the Underwater Harvesters Association (UHA) and the Department of Fisheries and Oceans (DFO) from July 7-18, 1994. The purpose of this survey was to estimate the current density of geoducks and to back-calculate the virgin density with catch data from harvest logbooks. Survey results will be considered in the process of quota calculations for the geoduck fishery in QCI. The virgin density calculated from this survey and from historical fishery records is lower than the 3.0 geoducks/m super(2) currently used for calculating quotas in the QCI. The average annual exploitation rate of 3.3% also indicates that current harvest levels may be too high. This conclusion may be tempered somewhat if the show factor corrections had lead to an underestimation of standing stock. An improvement in this aspect of geoduck survey methodology and more accurate measures of geoduck habitat would lead to improved accuracy of virgin density estimates.

Hand, C. M. and Dovey, G. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). A survey of geoduck populations in the Elbow Bank and Yellow Bank area of Clayquot Sound, west Vancouver Island, in 1994 and 1995. Can-Manuscr-Rep-Fish-Aquat-Sci; Rapp-Manuscr-Can-Sci-Halieut-Aquat. 1999; (2479):40. Abstract: A survey of geoduck (*Panopea abrupta*) stocks in a portion of Clayquot Sound, on the west coast of Vancouver Island, was conducted by the Underwater Harvesters Association and Fisheries and Oceans Canada in Sept. and Oct. of 1994 and 1995. The purpose of these surveys was to estimate the density of geoducks in known beds, establish and verify the boundaries of the beds and determine the age and weight distribution of the population from samples of geoducks collected. Virgin density was also calculated by reconstructing it from the survey density, the density of geoducks removed by the fishery and the density of recruited geoducks. Survey results are considered in the process of quota calculations for the geoduck fishery on the west coast of Vancouver Island. Results indicate that the geoduck bed on Yellow Bank and the bed on Morfee/Dunlap are, in effect, one continuous bed. As a result, the original estimate of the area of geoduck beds in the survey area, based on harvest.

Hand, C. M.; Hobbs, K., and Harbo, R. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Quota options and recommendations for the 1996 geoduck clam fishery. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1995-Part-1-Bivalves Waddell,-B.J.-(Eds); Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.) . 1998; (2214):375-434. Abstract: Geoduck (*Panopea abrupta*, Conrad 1849) stocks were examined for the North Coast, the west coast of Vancouver Island (WCVI), and the waters inside Vancouver Island (Inside Waters). The assessment methodology has not changed from previous assessments. It is a habitat-based approach where the area of geoduck habitat reported by fishers, estimated geoduck densities and mean weights, and an estimated sustainable harvest rate are incorporated into quota calculations. Changes in this year's assessment include the use of recent survey data for estimates of geoduck density, the use of new estimates of mean geoduck weight from commercial samples, and new measurements of harvest areas with modern digitizing equipment. The approach initiated in 1994 of reducing quotas where overharvesting had occurred, according to stock status relative to a 50-year cycle, was continued in the South Coast and extended to the North Coast. Similarly, the correction of landings reported on harvest logs with sales slip or port validator information was continued in the South Coast, as had been initiated in 1994, and extended to the North Coast. For the first time, a range of quota options is presented, based on the uncertainty around mean geoduck densities from survey data. Recommended low to high yield options range from 636,044-1,045,911 lb for Inside Waters, 775,108-2,195,952 lb for the North Coast and a single option of 781,135 lb for the WCVI. Low, medium and high range individual vessel quota recommendations are 39,860 lb, 55,377 lb and 73,145 lb, respectively, for 55 licenses. This represents a reduction of 53%, 34% and 13% from the 1995 fishery. The reduction in 1996 resulted from lower estimated mean densities, amortization of yields over a 50-yr fishing cycle and compensation for historical underreporting of catch.

Hand, C. M.; Marcus, K.; Heizer, S., and Harbo, R. (Department of Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Quota options and recommendations for the 1997 and 1998 geoduck clam fisheries. Invertebrate-Working-Papers-Reviewed-by-the-Pacific-Stock-Assessment-Review-Committee-PSARC-in-1996 Gillespie-G.E.-(Eds.); Walthers,-L.C.-(Eds.) . 1998; (2221):71-108. Abstract: Geoduck (*Panopea abrupta*) stocks were examined and quota options presented for the north coast, west coast of Vancouver Island, and waters inside Vancouver Island for 1997 and 1998. The assessment methodology is unchanged from previous assessments, where the area of geoduck habitat reported by fishers, estimated geoduck densities and mean geoduck weights form the basis of biomass estimates, and an estimated sustainable harvest rate is applied to derive quota options. In response to a request by fisheries for more stable quotas, data were compiled for two of the three rotational areas and equal quota options are presented for the 1997 and 1998 fisheries. Changes in biomass and quota calculations include updated geoduck density estimates from survey data, updated estimates of mean geoduck weight from commercial market samples, and new estimates of harvest areas from geoduck beds. The approach initiated in 1994 of reducing quotas where overharvesting had occurred, according to stock status relative to a 50-year cycle, was continued coastwide, as was the correction of landings reported on harvest logs with sales slip or port validator information. A range of quota options are presented, based on the uncertainty around mean geoduck densities from survey data, the variance around mean geoduck weights and the uncertainty around geoduck bed area.

Hand, C. M.; Vaughan, B. G., and Heizer, S. (Fisheries and Oceans Canada, Science Branch, Pacific Biological Station, Nanaimo, BC, Canada.). Quota options and recommendations for the 1999 and 2000 geoduck clam fisheries. Canadian Stock Assesment Secretariat. 1998.

Harbo, R. and Hobbs, K. eds. (Department of Fisheries and Oceans, Nanaimo, BC

[Canada] Sci. Branch). Pacific commercial fishery updates for invertebrate resources (1994). Can.-Manuscr.-Rep.-Fish.-Aquat.-Sci.-Rapp.-Manuscr.-Can.-Sci.-Halieut.-Aquat. 1997; (2369):186. Abstract: Fishery updates present catch and effort data and identify issues in the many invertebrate fisheries on the Pacific coast of Canada. These papers often form the basis for requests for stock assessment advice. There are more than 30 species of invertebrates exploited commercially and in 1993 the reported landings were 27,255 tonnes, a slight reduction from 1992 primarily due to quota reductions in the red sea urchin (*Strongylocentrotus franciscanus*) and geoduck clam (*Panopea abrupta*) fisheries. The landed value of invertebrates increased to approximately $80 million. This report has been organised by sections on molluscs, echinoderms and crustaceans. Specific gear types are identified in each section.

Harbo, R.; Thomas, G.; Hobbs, K., and Department of Fisheries and Oceans, Nanaimo BC Canada Fish. Branch. Quotas for the 1992 - 1993 geoduck clam fisheries. Can.-Manuscr.-Rep.-Fish.-Aquat.-Sci.-Rapp.-Manuscr.-Can.-Sci.-Halieut.-Aquat. 1993 No. 2179, 214 Pp. 1993; ISSN: ISSN 0706-6473. Abstract: The geoduck clam (*Panope abrupta*) fishery is managed by setting area quotas which are then equally divided for 55 Individual Vessel Quotas. The coast is divided into three license areas: north coast, southern inside waters and the west coast of Vancouver Island. A three year rotation of fishing areas was also implemented in 1989, with the I.Q. program to reduce the annual number of landing ports. It appears that the total harvest to date exceeds the current estimates of stock and production. This has been compensated in 1992 and 1993 by closures and quota reductions. Due to stock uncertainties, industry agreed to reduce the quotas but on the basis of a two year plan being set so that the industry could plan their fishery and market for product. Reductions of annual quotas by 15% each season for 1992 and 1993 were accepted by industry in 1991. A license will be moved each year from the west coast of Vancouver Island to the north coast. Over the period, 1992-1993 a scientific review of quota options is recommended prior to determining the 1994 quota. To determine the 1992-1993 quota options, the hectares of known commercial fishing areas were calculated and original densities were estimated as 1 geoduck /m super(2) for southern inside waters, 2 geoducks/m super(2) for the west coast of Vancouver Island and higher densities of 3.5 geoducks /m super(2) for beds in the north coast. Yield options of 1% were recommended for all areas in 1992 and 1993. There is a great uncertainty as to the stock size of subtidal geoduck clams.

Harbo, R. M.; Adkins, B. E.; Breen, P. A.; Hobbs, K. L., and Department of Fisheries and Oceans, Nanaimo B. C. Canada Pacific Biol. Stn. Age and size in market samples of geoduc clams (*Panope generosa*). CAN.-MANUSCR.-REP.-FISH.-AQUAT.-SCI. 1983. No. 1714, 81 Pp. 1983. Abstract: Eight lots of geoducs (*Panope generosa*), harvested by the commercial fishery were sampled at processing plants. Each individual was measured in shell length, shell weight, and total wet weight. The heaviest individual measured was 2198 g. Shells were collected and later aged with the acetate peel technique. Geoducs recruited to the fishery beginning at age 4, and appeared to be fully recruited by age 12. The mean ages in these samples varied from 28 at Tofino to 61 at Spider Anchorage. The oldest individual was 146 years old. Mortality rates calculated from age frequencies were found to range from M = 0.003-0.021. Growth rates determined from age, length and weight data, were similar to those found in other studies.

Harbo, R. M.; Peacock, S. D., and Department of Fisheries and Oceans, Nanaimo B. C. Canada Pacific Reg. The commercial geoduck clam fishery in British Columbia, 1976 to 1981. CAN.-MANUSCR.-REP.-FISH.-AQUAT.-SCI. 1983. No. 1712, 47 Pp. 1983. Abstract: Geoduck clams are harvested commercially by divers using hand-held high pressure water jets, guided and controlled underwater by a diver, to displace the substrate surrounding individual clams. The commercial geoduck fishery in British Columbia began in 1976 with five boats harvesting 97 thousand pounds (44 metric tons) from the Strait of Georgia. The fishery expanded rapidly until 1979 when entry was limited and harvest quotas were established at 4.5 million pounds (2042 t) for the South Coast district, and 3.5 million pounds (1588 t) for the North Coast. The 1979 harvest by 72 boats was 5.4 million pounds (2450 t), taken from the Strait of Georgia and the West Coast of Vancouver Island.

Heath, W. A. Developments in shellfish culture in British Columbia. ANNUAL-MEETING-OF-NATIONAL-SHELLFISHERIES-ASSOCIATION-PACIFIC-COAST-SECTION-AND-PACIFIC-COAST-OYTSER-GROWERS-ASSOCIATION. 1995; 14(1):228. CODEN: National Shellfisheries Association Pacific Section and Pacific Caost Oyster Growers Association, Seaside, Oregon (USA), 2-4 Oct 1994. Abstract: Diversification of the B.C. shellfish industry is advancing with a number of new species culture initiatives underway. Progress on culture of scallops, geoducks, east coast mussels, and pinto abalone, as well as advances in offbottom oyster harvesting methods are described. Scallop developments include successful hybridization of Japanese (*Patinopecten yessoensis*) and weathervane (*P. caurinus*) scallops for disease challenge studies, improved seed production strategies and subtidal bottom sowing trials. Geoduck culture research is currently focusing on nursery and growout methods for commercial application. Growout trials are also proceeding for Atlantic mussel (*M. edulis*) hatchery seed to examine commercial feasibility for culture in B.C. Preliminary studies for an abalone hatchery and growout facility are also underway. A mechanized harvesting system for offbottom cultured oysters has recently been tested and demonstrated. (DBO)

Herren, D. W. The effectiveness of predator exclusion tubes for growout of the geoduck clam, *Panopea abrupta*. J.-SHELLFISH-RES. 1993 Vol. 12, No. 1, P. 152. 1993. CODEN: 85. Annu. Meet. Natl. Shellfisheries Association, Portland, OR (USA), 31 May-3 Jun 1993; ISSN: ISSN 0077-5711. Abstract: Although hatchery techniques have been developed to produce geoduck clam seed, field trials for seed growout have met with limited success. Yields of less than 1% lead to a predator study and then to testing various predator exclusion devices. This report describes the success of using biodegradable fiber pulp tubes to protect geoduck seed from predation. Implication of this technique for geoduck culture are discussed.

Hershberger, William; Bentzen, Paul; Davis, Jonathan, and Shaklee, James. Geoduck Genetic Studies - Proposal to WA Sea Grant. 1997.

Holmyard, N. Shellfish farming on the Pacific Coast. Seafood-International-London [Seafood-Int]. 2000; 15(10):36-38. Abstract: The West Coast of Canada and the USA is home to a number of long-established commercial shellfish operations that specialize in bivalve culture and ongrowing. More recently, these companies have responded to their nations' demand for new aquaculture species and the creation of sustainable fisheries of over-fished species, by developing techniques to hatch and nurture species such as geoduck, abalone and sea urchin. In British Columbia, oyster, clam and scallop farming are firmly established, with several large operations based on Vancouver Island. Mussel farming is less well developed but a number of operations are being set up. However, it is extremely successful along the coast just over the US border, where the production of several farms amounts to about 1,200t annually.

Jamieson, G. S. (Department of Fisheries and Oceans, Nanaimo, B.C. (Canada). Pacific Biol. Stn). 1983 and 1984 invertebrate management advice, Pacific Region. CAN.-MANUSCR.-REP.-FISH.-AQUAT.-SCI. 1985; (1848):111 pp. Abstract: Biological advice given to resource managers by research scientists and biologists in November of both 1983 and 1984 is presented as a series of documents. Some other advisory manuscripts have been published elsewhere. The topics discussed here include a stock assessment of Barkley Sound shrimp, the effect of growth rate variability on minimum size restrictions for prawns (*Pandalus platyceros*), on-going scallop hatchery studies, a stock assessment of intertidal clams on Savary Island, ghost fishing by lost Dungeness crab (*Cancer magister*) traps, crab movement in the Fraser River delta, crab gear selectivity studies in Departure Bay, and an evaluation of geoduck (*Panope abrupta*) survey methodology.

Jamieson, G. S. and Department of Fisheries Oceans, Ottawa Ont. Canada Sci. Inf. Publ. Branch. Commercial catch sampling: A review of its usage in the management of contagiously distributed subtidal mollusc species. SAMPLING-COMMERCIAL-CATCHES-OF-MARINE-FISH-AND-INVERTEBRATES, L'-ECHANTILLONNAGE-DES-PRISES-COMMERCIALES-DE-POISSONS-ET-D'-INVERTEBRES-MARINS.- Doubleday,-W.G.;Rivard,-D.-Eds. 1983; (66):240-247; ISSN: ISBN 0-660-52448-1. 0706-6481. Abstract: The quality and usage in management of commercial cath sampling data are discussed for three major Canadian subtidal mollusk fisheries: sea scallop, *Placopecten magellanicus*, abalone, *Haliotis kamtschatkana*, and geoduc clams, *Panope generosa*. Atlantic sea scallop catch data have been collected since 1970, but the frequent inability to identify the precise fishing location of a subsample and the lack of a statistically rigorous sampling design impedes data usage. In British Columbia, both abalone and geoduc fisheries are relatively recent, and little catch sampling has occurred. The potential, value, and usage of commercial catch data in all three fisheries are discussed, and it is suggested that with present programs, commercial catch sampling of these species should be of low priority.

Jamison, D.; Heggen, R., and Lukes, J. Underwater video in a regional benthos survey. PROCEEDINGS-OF-THE-PACIFIC-CONGRESS-ON-MARINE-TECHNOLOGY,-HONOLULU,-HAWAII,-APRIL-24-27,-1984. 1984; Marine-Technology-Soc.,-Manoa,-HI-USA.-Hawaii-Sect 1984. pp. MRM1(15-17). CODEN: PACON '84: Pacific Congress on Marine Technology, Honolulu, HI (USA), 24-27 Apr 1984. Abstract: A regional survey using an underwater television system found that several species of large invertebrates not obtained by grab or trawl are extremely abundant. Based on biomass alone they dominate the benthic fauna. The survey was initiated because a commercial fishery exists for the large Geoduck Clam (*Panope generosa*) in shallow water (< 60 feet) of Puget Sound in the State of Washington. In order to determine whether populations of this clam existed in deeper waters, beyond SCUBA depth, an underwater television system was developed and utilized by the Department of Natural Resources to accomplish a regional survey of deepwater stocks and associated organisms. The camera is housed in a Jay-Mar underwater housing. The camera is mounted on a sled in a forward looking position about 50 cm above the bottom. Through the use of a video screen splitter, the underwater imagery is combined with a picture of various instruments so that the combination can be simultaneously viewed on a monitor in the cabin as well as recorded on a video recorder. The instruments are the Loran C, a digital clock, and a digital depth sounder.

Jeffs, A. 2003. Assessment of the Potential for Aquaculture Development in Northland. A report prepared for Enterprise Northland-Aquaculture Development Group. NIWA Client Report: AKL2003-012. 245 pp. This report offers a brief description of geoduck ecology and assesses its likelihood for future aquaculture efforts. Two species, *Panopea zelandica* and *Panopea smithae* occur in shallow waters located off sandy beaches throughout much of the country. Until recently, the larger species, *P. zelandica*, was harvested by divers in small quantities. Little is known regarding geoduck biology, aquaculture and enhancement. Research is currently underway to evaluate the potential for geoduck aquaculture, however it is postulated that this species may not be suitable given its slow growth rate and possible inability to be cultured at high densities.

Jo, M. K.; Byun, K. S.; Lim, K. B.; Son, S. J.; Lee, S. J.; Baik, C. I.; Park, Y. J.; Choi, S. H.; Hong, J. P.; Kim. G.Y.; Sung, K. T.; Lee, S. C., and Kwun, K. S. Distribution and ecology of major shellfishes in the coastal area of Kyongsangbuk-do. BULL.-NATL.-FISH.-RES.-DEV.-AGENCY-KOREA 1995 No. 51, Pp. 23-66. 1995; ISSN: ISSN 1225-6358. Abstract: An environmental survey and study of the distributional patterns of some important commercial Korean shellfish were carried out in the Kyongsangbuk-do coastal areas during 1991. The distribution patterns of the commercial species were characterized as follows. *Panope japonica* was mainly distributed in the coastal area between Puk-myon and Chukpyon-myon with 2.625 ha and its' vertical distribution layer was at 20-630 m; The sediment was composed of medium sand. *Gomphina melanaegis* showed a wide range of distribution patterns along the coastal areas of Puk-myon, Ulchin-gun, Hunghae-up and Yong-il-gun with 1.082 ha; It's vertical distribution layer was 2-8 m. The sediment consisted of fine sand. *Patinopecten yessonensis* in the coastal areas of Chikyeong, Janggi-gab and Yong-il-gun had a narrow distributional areas of 458 ha and its' vertical distribution layer was 30 m. The mesh size of sediment was fine sand. *Anadara broughtonii* inhabited the coastal area only near Yong-il-Gun with a vertical distribution layer of 20-30 m. The mesh size of sediment was silt. The distribution area was estimated about 3.335 ha. *Mactra chinensis* distributed along the coastal areas of Yeonan-gab, Imgok-dong and Yong-il bay with 172 hal; its' vertical distribution layer was 2-7 m. The sediment consisted of fine sand. The value of gonadosomatic index (GSI) of *P. japonica* showed the lowest in July as 10.2 and the highest in December as 17.2. The GSI value of *P. yessoensis* was the highest in July as 27.0 and decreased after August. The value of fatness of *M. chinensis* also increased from April as 15.1, highest in June, and decreased from July. The present biomasses of the above 5 shellfishes estimated by the swept-area method were 9,566.6 tonnes for *G. melanaegis*, 6,008.5 tonnes for *P. japonica*, 1,993.1 tonnes for *M. chinensis*, 87.1 tonnes for *A. broughtonii*, and 28.8 tonnes for *P. yessoensis*.

Johnson, K.; Davis, J.; Elston, R. A.; Cheney, D. P., and Suhrbier, A. D. Geoduck hatchery and production techniques. USDA Small Business Innovation Research Grant, Phases 1 and 2. Final Reports. 2002. 2002. Abstract: Preliminary/Exploratory research by Taylor Shellfish and PSI encompassed out of season broodstock maturation and conditioning, optimal types and rates of larval feed, larval setting mortality, and farming methods and predator exclusion. Phase 1 funding has been used in the development of experimental models and techniques. Phase 2 funding was being used to further develop the predator exclusion strategies, assess survival and carrying capacity of commercially planted sites, evaluate efficacy and environmental impacts of commercial harvest techniques, and to evaluate the feasibility of subtidal culture techniques making better use of extreme low tidal elevations.

Kang, S. H. and Jones, G. I. Studies of composition, quality changes, and utilization of the geoduck. Res-Fish-Coll-Fish-Univ-Wash. 1972; 1971(355):53-54. Abstract: A study was conducted of the factors associated with harvesting, preparation for market and preservation and storage of the geoduck clam. The percentage composition of edible and nonedible portions of the clam, and the percentage composition of protein, fat, minerals and moisture, of the edible portion are given. Keeping qualities under various conditions are given. Canning recipes prepared for organoleptic evaluation indicate that many variations of marketing and preparation for the consumer will be possible.

Ketchen, K. S.; Bourne, N., and Butler, T. H. History and present status of fisheries for marine fishes and invertebrates in the Strait of Georgia, British Columbia. CAN.-J.-FISH.-AQUAT.-SCI. 1983. Vol. 40, No. 7, Pp. 1095-1119. 1983. CODEN: Symposium on the Fisheries and Oceanography of the Strait of Georgia, Pacific Biol. Stn., Nanaimo, B.C. (Canada), 18 Feb 1982. Abstract: An historical account is given of the development of Strait of Georgia commercial fisheries (other than salmon) from their beginnings in the middle to late 19th century to the 1980s. Where possible, attempts were made to explain past fluctuation in abundance, especially to distinguish natural effects from those of fishing or socioeconomic origin. The review deals with commerical exploitation of herring (*Clupea harengus pallasi*), dogfish (*Squalus acanthias*), lingcod (*Ophiodon elongatus*), Pacific cod (*Gadus macrocephalus*), English sole (*Parophrys vetulus*), pollock (*Theragra chalocgramma*), hake (*Merluccius productus*), Dungeness crab (*Cancer magister*), shrimps (*Pandalopsis dispar*, *Pandalus platyceros*, *P. jordani*, *P. hypsinotus* and *P. danae*), oyster (*Crassostrea gigas*), butter lams (*Saxidomus giganteus*), little neck clams (*Protothaca staminea*), Manila clams (*Tapes phillipinarum*), geoduck clams (*Panope generosa*) and other invertebrates. Lingcod and the various shellfish species are also the object of recreational fisheries.

Kim, H. S.; Park, Y. J.; Kim, W. K.; Chang, J. W., and Kim, J. D. Studies on ecology and growth of *Panope japonica* in shore of Kangwon Province, Korea. BULL.-NATL.-FISH.-RES.-DEV.-AGENCY-KOREA. 1991. No. 45, Pp. 269-282. 1991. Abstract: An autecological survey of *Panope japonica* was carried out at Kumjin in the eastern coast of Korea from April 1989 to March 1990. The species was found to inhabit deep water, mainly in 29-35 m depth, and burrow into sandy bottoms. The concentration of PO sub(4)-P and DIN varied in range of 0.28-0.70 mu g-at/l and 1.98-3.68 mu g-at/l respectively. Based on the monthly variation of gonad somatic index, the spawning period was estimated to be from January to April. The ring where the translucent zone shifts to the opaque one was regarded as an annulus. The time of its formation was estimated by monthly variations of marginal growth rate in the shell. It was formed once a year over the period from April through May. From analysis mean shell length at the formation of the annulus, von Bertalanffy's growth equation was calculated.

King, G. Operations at Taylor Seafood. Journal-of-Shellfish-Research. 2000; 19(1):575. CODEN: 20. Annual Milford Aquaculture Seminar, Milford, Connecticut (USA), February, 2000. Abstract: Taylor United, Inc. has been growing *Mytilus galloprovincialis* for approximately ten years. Presently we market about 800,000 pounds per year. All production is hatchery seed based and grown out on rafts with average spawn to harvest of 16-18 months. The company also produces about 140,000 gallons of shucked oysters, one-million dozen single oysters and 3,000,000 pounds of manila clams. Recently, Taylor Seafood has been planting two million geoduck seed a year and should start harvesting significant volumes in the next two years. The company has a hatchery in Quilcene, Washington, a floating upwell nursery in Shelton, Washington, a leased hatchery in Tillamook, Oregon and a hatchery nursery in Kona, Hawaii. We also recently started a scallop farm in Mexico. These operations will be described in the presentation.

King, T. and Beattie, H. Volunteers can do more than dig a duck. Journal-of-Shellfish-Research. 1998; 17(4). CODEN: International Conference on Shellfish Restoration Hilton Head Island, South Carolina (USA); ISSN: ISSN 0730-8000.

Abstract: Geoduck clams, often called gooey ducks or G.O. ducks, are perhaps the most talked about clam species by visitors to the Pacific Northwest. The geoduck's native range is from Baja, California to Alaska from the +3 foot tidal height to -400 feet deep, and lives for over 100 years. The cultivation of geoducks has been underway in Washington State since 1970. With the cultivation of hatchery seed and the development of predator exclusion devices, enhancement of public beaches is a viable venture. Currently, the enhancement of recreational beaches generally yields a 20 -40% survival rate. However, the labor needed to install the exclusion devices can often make the enhancement time consuming and expensive. Since 1996, Washington Sea Grant and the Washington Department of Fish and Wildlife have been working together to involve groups such as 4H, Boy Scouts, Girl Scouts and community members to help enhance local recreational beaches. This effort has lead to fun filled geoduck planting adventures. To date over 1,400 hours of volunteer work have been logged to plant 38,000 geoducks. The successful recruitment and management of volunteers is essential to this program since installing the geoduck "condos" and planting the geoducks are but one aspect of the enhancement effort. Retrieving the condos after a year and patrolling the planted areas for human predators and polluters over the next 4 to 5 years are other important volunteer functions. Working together to support geoduck enhancement efforts has lead to increased recreational opportunity and heightened awareness of the marine environment.

Kuons, R. R.; Cardwell, R. D., and Washington Dep. Fisheries, Olympia USA. Significant areas for certain species of food fish and shellfish in Puget Sound. TECH.-REP.-WASH.-DEP.-FISH. OLYMPIA,-WA-USA-WDF 1981. 49 Pp. 1981. Abstract: Many species of marine organisms, including economically important fish (food fish) and invertebrates (shellfish), are partially or totally dependent upon intertidal and subtidal habitats for growth, reproduction, and viability. These are requirements that must be considered in managing the numerous uses of marine shorelines. A series of maps were compiled that graphically delineate the documented occurrence of certain species of food fish and shellfish in the greater Puget Sound Basin east of Freshwater Bay. These areas are considered significant to the survival and harvestability of the following: Pacific herring (*Clupea harengus pallasi*), surf smelt (*Hypomesus pretiosus*); hardshell clams, geoduck clams (*Panope generosa*); Pacific oyster (*Crassostrea gigas*) and Olympia oyster (*Ostrea lurida*). The maps describe only the species mentioned and delineate merely a fraction of the populations simply because most of the state's marine waters remain to be comprehensively surveyed.

Leitman, A. R. The past, present and future of geoduck (*Panope abrupta*) seeding efforts in Puget Sound. J.-SHELLFISH-RES. 1989. Vol. 8, No. 2, P. 414. 1989. CODEN: 43. Annu. Meet. of the Pacific Coast Oyster Growers' Assoc. and Natl. Shellfisheries Assoc. (Pacific Coast Section), Seattle, WA (USA), 21-23 Sep 1989; ISSN: ISSN 0077-5711. Abstract: Hatchery seed of *Panope abrupta* from the Point Whitney Shellfish Laboratory have been planted in Puget Sound since 1976. The slow recruitment and fast growth rate of these bivalves make them extremely amenable candidates for re-seeding efforts in previously harvested areas. The first experiments used relatively small seed and were planted directly from the hatchery. Only a small percentage of the seed were recovered. In later years the seed was transferred from the hatchery to a nursery facility which allowed the geoduck seed to be planted at a larger size; these seed afforded greater success. Areas that have been sampled 2 years post-seeding are discussed in terms of their successes and failures of both the planting and sampling methods.

Milne, M. and Ketler, J. Review of student studies on juvenile geoducks at Malaspina University College's fisheries and aquaculture program. Journal-of-Shellfish-Research. 1998; 17(4). CODEN: 52. Annual Meeting: Pacific Coast Oyster Growers Association and National Shellfisheries Association, Nanaimo, BC (Canada), 14-16 Oct 1998. Abstract: Since 1994 a series of studies have been conducted by the Fisheries and Aquaculture Program at Malaspina University/College on the Pacific geoduck, *Panopa abrupta*. These studies supported by Fan Seafoods Ltd, have included: morphometric relationships, orientation and digging behaviour, effects of crab predation, salinity tolerance tests, and most recently a study of moonsnails as predators of juvenile geoducks. The first moonsnail study was designed to assess predation mode and rate by the Arctic moonsnail, *Cryptonatica affinis*, on juvenile geeoducks. The results indicated that Arctic moonsnails (shell diameter 28-30 mm) did prey on geoducks (28-30 mm shell diameter) at a rate of 1.5-2.5 geoducks per moonsnail/week. The snails either bored into the geoduck shell or apparently digested the entire juvenile without boring. A second study assessed the Lewis's moonsnail, *Polinices lewisii*, as a predator of juvenile geoducks and was also designed to compare food preferences between geoducks and the Manila clam, *Tapes philippiunarum*. The moonsnails used averaged 103 mm shell length, the manila clams 30-50 mm, and the geoducks 15-21 mm. The observed predation rates were very low for both species of clams and further trials are needed to clarify the importance of the Lewis's moonsnail for geoduck aquaculture.

Miyauchi, D.; Patashnik, M., and Kudo, G. Fish protein used to bind pieces of minced geoduck. Proc-Natl-Shellfish-Assoc. 1973; 63p. 9. CODEN: Natl. Shellfisheries Association Convention (Pacific Coast Section), Williamsburg (Virginia), 25-29 Jun 1972. Abstract: In 1970 when the State of Washington started leasing subtidal geoduck beds for commercial harvesting, our lab in cooperation with the Washington State Department of Fisheries obtained yield data, palatability scores, and information on cold-storage characteristics of the various edible components of the geoduck. The fledgling geoduck processing industry, which consists of 4 or 5 small processors, requested our aid in finding a suitable binder with which to make marketable patties out of the trimmings from their prime geoduck steaks. In response to this request, we prepared frozen blocks of minced geoduck, using our fish binder made from rockfish flesh and common food ingredients. Breaded portions prepared from 1/4 and 1/2 in. thick slices from the blocks were judged to be an improvement over those now being prepared commercially. The experimental samples held together well during deep-fat frying and pan frying. Samples of experimental blocks have been given to the various geoduck processors for their evaluation and modification.

Nishitani, L., and K. K. Chew. 1988. PSP toxins in the Pacific coast states: monitoring programs and effects on bivalve industries. Journal of Shellfish Research 7: 653-669. The authors describe changes in the distribution and frequency of PSP toxicity in California, Oregon, Washington and Alaska. The expansion of PSP throughout Puget Sound from the Strait of Juan de Fuca to the Southern Basin from the late 1970s to1980s is described. In Puget Sound, onset of summer blooms were found to depend on the development of favorable surface water temperatures to a depth of several meters, particularly in the absence of wind turbulence. Limited nitrogen and phosphorus were also found to control the onset and duration of blooms. At the time of publication, the geoduck fishery was believed to be unaffected by PSP because the gut portion was the only part of the clam exceeding the 80 µg STX eq/100 g regulatory limit.

Noakes, D. J. and Campbell, A. Use of Geoduck clams to indicate changes in the marine environment of Ladysmith Harbour, British Columbia. Environment. 1992; 3(1):81-97.

Orensanz, J. M. Lobo; Hilborn, Ray, and Parma, Ana M. Harvesting Methuselah's clams-Is the geoduck fishery sustainable, or just apparently so? 1999.

Pease, B. and Cooper, K. A relationship between selective larval settlement and adult distribution patterns of geoduck clams and the presence of chaetopterid polychaete tube mats in Puget Sound, Washington. J.-SHELLFISH-RES. 1988. Vol. 7, No. 1, P. 129. 1988. CODEN: 1986 Annu. Meet. of the National Shellfisheries Assoc., Seattle, WA (USA), 22 Jun 1986; ISSN: ISSN 0077-5711. Abstract: Visual observations during subtidal diver survey of geoduck clam *Panope abrupta* beds revealed the epibenthic mats of intertwined tubes of the chaetopterid polychaete species *Spiochaetopterus costarum* and *Phyllochaetopterus prolifica* commonly occur with geoduck clams in Puget Sound. Of 56 macrofauna species commonly observed during subtidal surveys, *S. costarum* and *P. prolifica* co-occurred with geoduck clams more frequently than any other species. The density of geoduck clams was significantly higher in transects where the chaetopterid polychaetes occurred. Competent geoduck clam larvae metamorphosed in response to tubes of *S. costarum*, *P. prolifica* and *Diopatra ornata*, but not in response to tubes of *Onuphis elegans*; they respond to chemicals from the precipitate and supernate of a seawater extract of *S. costarum* and to the amino acid L-Dopa. Findings suggest that the epibenthic mat of tubes formed by *S. costarum*, *P. prolifica*, and *D. ornata* in Puget Sound identify a habitat where the probability of survival or recruiting geoduck clams is increased.

Phipps, B. Geoduck planting and grow-out trials. Clam-and-Oyster-Farming Nosho,-T.-(Ed.) Washington-Univ,-Seattle-USA-Sea-Grant-Program. 1998; p. 56. CODEN: 7. Conf. for Shellfish Growers: Clam and Oyster Farming, Olympia, WA (USA), 3-4 Mar 1997. Abstract: After we receive the seed from the hatchery we have two methods of planting. One is with car cover and the other is with tubes. Car cover is the fastest way to plant geoducks. There are different sizes of car cover that you can use: 1/4 in., 1/2 in., and 3/4 in. mesh. To plant seed and use car cover, we trench ditches 6 inches deep around the edges of the net. After making the trench we rake the ground to create little furrows. This helps get any leftover crabs and makes little valleys for the seed to settle into. For 1/4-inch mesh or larger, you can lay mesh down, bury the edges, then plant the seed straight through the net. For smaller than 1/4-inch mesh, you have to lay the animals down first, then carefully pull the net over them and bury the edges. We experienced several problems with car cover. If you plant on a windy day, the animals may be blown onto a section of the cultivated area. This results in too many animals in one area and they will not grow as fast as you want them to. Netting also rips in really bad weather. Another time, we had geoduck necks get caught in the netting and the constant pull actually pulled them out of the ground. Survival using car cover has been hit and miss. Sometimes we plant and get good survival. Other times we plant and get lousy survival. The next method of planting is with tubes. Tubes are time-consuming. You have to individually cut your pipe into 9- to 10-inch lengths and push them into the ground.

Poole, R. Hatchery rearing of the geoduck clam (*Panopea abrupta*). Clam-and-Oyster-Farming Nosho,-T.-(Ed.) Washington-Univ,-Seattle-USA-Sea-Grant-Program . 1998; 50-51. CODEN: 7. Conf. for Shellfish Growers: Clam and Oyster Farming, Olympia, WA (USA), 3-4 Mar 1997. Abstract: This paper describes methods used to rear geoducks. Most techniques are modified from those used in oyster and clam culture. For the information in this paper, the author relied heavily on the experience of other hatcheries, particularly the Washington Department of Fisheries and Wildlife (WDFW) laboratory at Point Whitney. Geoduck larvae have been reared at the Lummi Shellfish Hatchery on several occasions. Juveniles were produced by two different methods, both of which will be described. Hatchery rearing of the geoduck clam is a relatively new venture. WDF&W (formerly the Washington Department of Fisheries or WDF) has been involved in a program of geoduck enhancement since 1981 using hatchery techniques developed for oyster and clam culture. An original goal of the enhancement project, conducted in cooperation with the Department of Natural Resources (DNR), was to double geoduck landings in Puget Sound. It was estimated that reaching this goal would require planting 30 million geoduck seed per year. Funding for the project was to be provided by lease fees paid by divers harvesting geoduck on DNR tracts.

Pritchett, Marc (Alaska Department of Fish and Game). Management Plan for the Harvest of Geoduck Clams *Panopea abrupta* in Southeast Alaska. 1999; 1J99-39.

Reid, R. G. B. (Washington Univ., Seattle (USA). Sea Grant Program). Feeding behavior of early juvenile shellfish, with emphasis on the Manila clam. [Nosho,-T.Y.;Chew,-K.K.-eds.]. REMOTE-SETTING-AND-NURSERY-CULTURE-FOR-SHELLFISH-GROWERS:-WORKSHOP-RECORD. 1991; 50-54. CODEN: Remote Setting and Nursery Culture for Shellfish Growers: Workshop, Olympia, WA (USA), 19 Feb 1991; ISSN: ISBN 0-934539-15-4. Abstract: In many bivalve species there is a distinctive postmetamorphic alteration of feeding behavior. The filter feeding mechanisms of the pediveliger are lost at metamorphosis, and there is a pause before the gills develop sufficiently to allow the resumption of filtration. The delay may be no more than a few hours in oysters, the most widely maricultured bivalve type. However, in several commercially significant species the delay may last for a few days to a few weeks, and in failing to recognize this fact some standard nursery practices may contribute to setting and post-setting mortalities. Understanding bivalve pedal feeding should be valuable in designing appropriate feeding regimes for early juveniles. Pedal feeding modalities in a number of bivalves, including *Corbicula fluminea*, *Fimbria fimbriata*, *Mysella*, *Musculus*, *Miodontiscus*, *Geloina*, *Tridacna*, *Panope*, *Tapes*, *Patinopecten*, *Crassadoma*. A downwelling system providing suspended, mixed algae is tested for juvenile Manila clams (*Venerupis japonica*).

Rensel, J. 1993. Factors controlling paralytic shellfish poisoning (PSP) in Puget Sound, Washington. Journal of Shellfish Research. 12(2): 371-376. This paper discusses the physical and chemical factors that contribute to the growth of *Alexandrium catenella* in Puget Sound given the assumption that cell toxicity may or may not be closely related to these factors. Favorable surface and subsurface water temperatures (13-14 °C), absence of vertical mixing in summer months and adequate nitrogen concentrations are believed to support *A. catenella* growth. Mixing zones caused by subsurface semi-blocking sills at the mouth of Hood Canal and Nisqually Reach and nutrient depletion in poorly flushed waters may be partly responsible for the low incidence of toxic blooms in southern Puget Sound.

Roberts, T. L. and Shuman, F. R. Development of an intertidal technique for growing geoducks, *Panope abrupta*, in the Pacific Northwest. NORTHWEST-ENVIRON.-J. 1989. Vol. 5, No. 1, Pp. 167-179. 1989. Abstract: The purpose of the described research is to develop a commercial technique for the intertidal culture of the geoduck clam (*Panope abrupta*). The existence of a strong market for geoducks and recent advances in hatchery rearing techniques have made such a project timely and feasible.

Russell, S. and Keeley, N. (Malaspina University College In conjunction with IEC and FAN seafoods). The Geoduck clam. 1994. Abstract: A report that reviews current (1995) methods and experiments in Geoduck culture

Shaul, W. and Goodwin, L. Geoduck (*Panope generosa*: Bivalvia) Age as Determined by Internal Growth Lines in the Shell. CAN.-J.-FISH.-AQUAT.-SCI. 1982; 39(4):632-636; ISSN: ISSN: 0706-652X. Abstract: Geoduck (*Panope generosa*) age was determined by counting internal growth lines in the hinge plates of the shells. Several experiments substantiated the hypothesis that one growth line is deposited every year. Growth line deposition was found to occur during the winter.

Shaul, W. J. Postharvest estimation of the harvestable biomass of the Pacific geoduck clam *Panope generosa* Gould in an area in Puget Sound, Washington. J.-SHELLFISH-RES. 1985. Vol. 5, No. 1, Pp. 53-54. 1985. CODEN: Annu. Meet. National Shellfisheries Association, West Coast Section, Bellingham, WA (USA), 7 Sep 1984; ISSN: ISSN 0077-5711. Abstract: Methods for estimating the harvestable biomass of geoduck clams *Panope generosa* in a delineated area any time after an initial harvest are presented. Efficient management of the geoduck fishery requires the knowledge of the length of the period between successive harvests of an area. Variable recruitment rates and variable periods were used for recovery in an equation for estimation of harvestable biomass. Data for the calculations were from a geoduck population near Dougall Point. Puget Sound, Washington. Geoduck biomass never reached harvestable levels at a recruitment rate of 0.01 recruits/m super(-2)/yr super(-1), the recruitment rate estimated for the population over the last 20 yr. A recruitment rate of 0.23 recruits/m super(-2)/yr super(-1), the highest rate estimated for the population during the last 100 yr resulted in a harvestable biomass exceeding the preharvest biomass, 2963 g/m super(-2), in less than 20 yr. Recruitment rates estimated for past data indicate the variability that could occur in the future recovery of a bed to harvestable biomass.

Short, Kent S. and Walton, Raymond (Ebasco Environmental). The Transport and Fate of Suspended Sediment Plumes Associated with Commercial Geoduck Harvesting - Final Report. Prepared for State of Washington Department of Natural Resources. 1992.

Shuman, F. R. and Roberts, T. L. Biological feasibility of intertidal aquaculture of the geoduck clam, (*Panope generosa*). J.-SHELLFISH-RES. 1989. Vol. 8, No. 2, P. 416. 1989. CODEN: 43. Annu. Meet. of the Pacific Coast Oyster Growers' Assoc. and Natl. Shellfisheries Assoc. (Pacific Coast Section), Seattle, WA (USA), 21-23 Sep 1989; ISSN: ISSN 0077-5711. Abstract: The project goal was to test the feasibility of intertidal culture of geoduck clams (*Panope generosa*). Seed clams, obtained from a shellfish hatchery at the Point Whitney Shellfish Laboratory, were planted in the bottom under netting and in nursery tubs filled with screened substrate and covered with netting. Growth trials were run in 4 intertidal sites in Washington State. In-bottom plantings were unsuccessful in 3 of 4 sites, mostly due to very high initial mortality. Growth and survival at the fourth site were encouraging. The nursery tub plantings were successful at all sites, showed close to 100% survival and promise an efficient method for nursery rearing and final growout of geoduck clams. Recommendations are given for planting strategies and commercial growout techniques.

Sizemore, Bob (Washington Department of Fish and Wildlife). Status of the Commercial Geoduck Clam Fishery in Washington State and Two Listed Salmon Populations, Hood Canal Summer Run Chum Salmon and Puget Sound Chinook Salmon. Draft. Brinnon, Washington; 1999; Memorandum to the National Marine Fisheries Services from the Washington State Departments of Natural Resources and Fish and Wildlife for consideration of fishing activity under the federal Endangered Species Act.

Skog, Michael. Geoduck Fishermen Ensure Their Own Future.

Sloan, N. A. and Department of Fisheries and Oceans, Nanaimo B. C. Canada Pacific Biol. Stn. Feasibility of improving geoduck stock assessment: History of the problem, recommended methods and their costs. CAN.-MANUSCR.-REP.-FISH.-AQUAT.-SCI. 1985. No. 1848, Pp. 57-67. 1985; ISSN: ISSN 0706-6473. Abstract: The history, methods, and problems with geoduck, *Panope abrupta*, stock assessments in British Columbia and Washington State are recounted. Methods are diving surveys in shallow water and remote sensing in deep (> 18.5 m) water. Objectives for improving stock estimates in British Columbia are discussed and a shallow water diving system using a belt transect (2 x 25 m or 2 x 50 m) as the sampling unit is recommended. Costs are estimated for the system and compared with those incurred by Washington State workers in the management of their fishery. Because of its expense and relatively low accuracy, remote sensing is recommended for qualitative exploration of new areas only.

Turner, K. C. and Cox, R. K. Seasonal reproductive cycle and show factor variation of the geoduck clam *Panope generosa* (Gould) in British Columbia. J.-SHELLFISH-RES. 1981. Vol. 1, No. 1, P. 125. 1981. CODEN: Annu. Meet. of the National Shellfisheries Association, Hyannis, MA (USA), 9 Jun 1980. Abstract: Geoduck clams, *P. generosa* (Gould), were collected on a monthly basis from Cherry Point, Saanich Inlet, 35 km north of Victoria, and gonads analyzed for reproductive phase. Samples were harvested from May 1977 to August 1978, at a depth of 9 m. The reproductive cycle was divided into five phases: early active, late active, ripe, partially spent, and spent. Four 100-m super(2) plots wer simultaneously observed to determine what percentage of the population were visible at various times of the year. Gametogenesis was observed first in September samples and by early January, 98% of the clams were in the early active phase. Six percent were ripe already. Most ripe specimens occurred during April (54%) and May (91%). Spawning began in May, and by June, 77% of the samples were partially spent. Siphon-show factor increased rapidly from February to April and remained at a high, but reduced level during the summer months. Shows decreased in the fall, and in January monitoring, no animals were observed in any of the four plots.

Vadopalas, B. A. and Davis, J. P. Induction of triploidy in the geoduck clam, Panope abrupta. Journal-of-Shellfish-Research. 1998; 17(4). CODEN: 52. Annual Meeting: Pacific Coast Oyster Growers Association and National Shellfisheries Association, Nanaimo, BC (Canada), 14-16 Oct 1998. Abstract: The development of geoduck culture techniques coupled with increased market demand led to cultured intertidal geoduck beds. Concerns then arose regarding the potential genetic risk posed by the reproductive contribution of hatchery outplants to wild stocks that may be genetically different. Although an ongoing study to determine the genetic stock structure of Puget Sound geoducks has yet to yield definitive results, the development of techniques to produce sterile triploids would enable geoduck culture to proceed irrespective of any genetic differences found. Moreover, triploid geoducks may exhibit an increased growth rate. Geoduck eggs were fertilized and distributed among three temperature and three salinity treatments to test the effects of these factors on the timing and synchrony of meiotic events. Samples were taken at 5 minute intervals to measure proportions of eggs at each meiotic stage. These data indicated a temperature and salinity combination for optimal triploidy induction of 15 degree C and 30 ppt., with the meiotic period between expulsion of the first and the second polar body lasting 20 minutes, beginning at 50 minutes post fertilization. We also investigated two chemical treatments, cytochalasin B (CB) and 6-dimethylaminopurine (6-DMAP), to evaluate their suitability for triploid induction in geoducks. We found optimal triploid induction (>95%) resulted from a 600 M 6-DMAP treatment using our optima. Preliminary data indicates survivorship to straight hinge was about 20%. Survivorship to metamorphosis was highly variable among groups, which could not be attributed to a single factor. Surviving triploid geoducks have been outplanted to evaluate growth and survivorship.

Valero, Juan L. Population Dynamics of the Geoduck Clam (*Panopea abrupta*). Ph. D. Research Project.

Velasquez, D. E. Shell fragility and its implications for the geoduck enhancement program. WORLD-AQUACULT. 1993; 24(3):34-38; ISSN: ISSN 1041-5602. Abstract: Variability in shell thickness of geoduck clams (*Panopea abrupta*) produced in nurseries on Puget Sound, Washington (USA) was associated with shell breakage which in turn impaired seed performance in a simulated planting. Shell thickness varied significantly between nursery groups of geoduck seed clams and was associated with high water temperatures and excessive benthic organics early in the rearing period. Thin shells were associated with a high incidence of shell breakage and seriously impaired survival.

---. Shell fragility in juvenile geoducks (*Panopea abrupta*) and its implications for the geoduck enhancement program. AQUACULTURE-'-92:-GROWING-TOWARD-THE-21st-CENTURY. 1992; 223. CODEN: Aquaculture '92, Orlando, FL (USA), 21-25 May 1992. Abstract: Geoduck (*Panopea abrupta*) clams are cultured to be planted subtidally to enhance recruitment of harvested populations in Puget Sound. One problem is the tendency of the shells to break upon removal from the nursery, varying from 7-60% breakage depending on the nursery group and the harvesting method. Thin-shelled groups are less than half as thick as their thick-shelled counterparts. An experiment tested the performance of broken-shelled seed clams in a simulated planting. Three populations possessed intact shells (IS) and three populations possessed broken shells (BS). Burial was monitored and exposure to crab predators (*Cancer productus*) followed. A staged excavation determined the number of surviving clams and their depth stations in the substrate. Results indicate the number of IS clams which avoided predation (63%) was significantly greater than BS clams (10%). Compared to the BS survivors, a greater proportion of IS survivors was found deeper in the substrate (76-152 mm and 152-228 mm depth stations). A strategy for reducing shell breakage is essential to increasing survival of planted juvenile seed geoduck.

Waddell, B. J. eds; Gillespie G.E. (eds.), and Walthers, L. C. eds. (Department of

Fisheries and Oceans, Nanaimo, BC [Canada] Sci. Branch). Invertebrate Working Papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. Part 1. Bivalves. Can-Tech-Rep-Fish-Aquat-Sci; Rapp-Tech-Can-Sci-Halieut-Aquat . 1998; 2214438 pp. Abstract: Working Papers prepared in 1995 by Fisheries and Oceans Canada staff, First Nations and industry representatives that were reviewed by the Pacific Stock Assessment Review Committee (PSARC) are presented. These documents form the basis of biological advice given to managers for the development of fishing plans for 1996. Topics included: results of depuration harvest surveys for intertidal clams (primarily Manila clams, *Tapes philippinarum*, and littleneck clams, *Protothaca staminea*); population assessments of butter clams (*Saxidomus giganteus*) at Seal Island and Manila clams at Savary Island; methodology for intertidal clam surveys; two geoduck (*Panopea abrupta*) surveys conducted in 1994; analysis of landed weight information from the geoduck fishery; and quota recommendations for the 1996 geoduck fishery.

Washington State Department of Natural Resources. Evaluation of the Intensive Management Program for the Geoduck Resource; 1984.

Washington State Department of Natural Resources (Washington State Department of Natural Resources). Should the Department authorize use of state-owned aquatic lands for geoduck aquaculture?; 2003 Apr 14.

Weiss, S. Ugly? -- you bet ... but the geoduck fishery persists despite limited markets, strict regulation, and difficult harvesting methods. WEST.-FISH. 1982. Vol. 104, No. 2, Pp. 13-15,30. 1982; ISSN: ISSN 0043-3721. Abstract: The British Columbia geoduck (*Panope generosa* fishery is described. Management of the fishery and some fishery regulations are discussed.

Westley, R. E. (Washington State Dep. Fish., Brinnon, WA, USA). The present status and future outlook of shellfish farming in Puget Sound, Washington. /[Presented at-: NSA Convention; Maryland (USA); 1975]. Proc.-Natl.-Shellfish.-Assoc.,-Md. 1976; (66):106. CODEN: Presented at-: NSA Convention Maryland (USA) 1975. Abstract: Shellfish farming in Puget Sound, Washington, involves principally culture and harvest of oysters, and harvest of natural crops of clams and geoducks. Present trends are decreasing production of oysters with some increase in clams and geoducks. Biologically, Puget Sound has enormous potential for increased production of oysters and geoducks due to the abundance of well protected, clean, nutrient rich water. Economic conditions have had a major impact on the oyster industry and economic conditions appear to be the major reason for the decline. Economic conditions appear favourable for the clam and geoduck fisheries. Recent enactment of legislation for control and management of shorelands has had some adverse effect of conduct of the shellfisheries and, depending upon further application of these laws, could be a major impediment in conduct of the shellfisheries in Washington State.

Wray, T. Geoduck fishermen secure their future. Fish-Farming-International [Fish-Farm-

Int] 2000 Vol. 2000; 27(4):36. Abstract: British Columbia's geoduck clam fishermen have invested in their future by initiating and funding a long-term enhancement programme in which seed (baby geoducks) are planted and monitored to augment wild populations.

You, B. J.; Jeong, I. H.; Lee, K. H., and Choi, H. G. Quality and storage stability of frozen geoduck *Panope japonica* (A. Adams). BULL.-KOREAN-FISH.-SOC. 1993 Vol. 26, No. 6, Pp. 549-556. 1993; ISSN: ISSN 0374-8111. Abstract: To obtain a basic data of Korean geoduck (*Panope japonica*) for fast food manufacturing, contents of proteinous compounds, nucleic acid and related compounds were analysed, and monthly changes of proximate compositions and freshness changes during frozen storage have been studied. The edible portions were 29.92% in 3 years old samples and 38.04% in 5 years old ones, respectively. The moisture and protein content showed the highest level from March to April and those of lipid and glycogen showed the highest level in July. Taurine, glycine, alanine and glutamic acid were the major free amino acid in 5 years old samples harvested in July and taurine content showed the highest level among free amino acid. Glutamic acid was the most abundant amino acid among the amino acids of protein hydrolyzate in 5 years old samples. Leucine and lysine were revealed as relatively higher content. Blanching at 95 multiplied by C for 2 mins was effective to maintain the quality of geoduck during frozen storage. Total creatine content was not changed in blanched geoduck.

12. ANNOTATED BIBLIOGRAPHY (Baywater, Inc.)

An annotated bibliography of published and unpublished reports relating to specific aspects of geoduck physiology, growth, and life history is provided below.

Cole, L., Beattie, J.H. and Chew, K.K. 1991. Geoducks (*Panope abrupta*) in a sand substrate nursery. Pp 55-56. In: Nosho, T.Y. and K.K. Chew (eds.), Remote setting and Nursery Culture for Shellfish Growers Workshop Record, WA State Sea Grant Program. Report considers use of algae that typically coats surfaces (*Tetraselmis suicica*) and algaes that are typically suspended in the water column (*Chaetoceros muelleri*) in a sand-based nursery system for juvenile geoducks. Preliminary information suggested that substrate based food supplies translated into better growth in geoducks than did treatments with suspended food supplies. From a physiological perspective, this report was the first to consider pedal palp feeding behavior and unique physiology of post settlement geoduck clams.

Cooper, K. and B. Pease. 1988. A relationship between selective larval settlement and adult distribution patterns of geoduck clams and the presence of chaetopterid polychaete tube mats in Puget Sound, Washington. J. Shellfish Research 7(1): 129 (abstract and unpublished manuscript). Chemical cues emanating from the tubes of polychaetes appeared to trigger settlement and subsequent metamorphosis of competent geoduck larvae onto the tubes of *Spiochaetopterus costarum* and *Phyllochaetopterus prolifica* and *Dioptera ornata*, often found in association

with adult geoduck beds. It was suggested that larvae may be induced to settle and metamorphose in the presence of these polychaetes, or the mats themselves. In fact, the relationship between polychaetes and geoducks may be more complex. Artificially developed geoduck beds in an intertidal region of Hood Canal were colonized by large numbers of chaetopterid polychaetes in 2002, suggesting that the presence of geoducks in fact induces the settlement of polychaetes to the area; that larvae may settle out in the presence of polychaete tube mats may be either coincidental or a co-evolved mechanism contributing to the structure of geoduck beds. In either case, physiological mechanisms utilized by larvae or small juveniles to facilitate final settlement in habitats favorable for survival and related to specific chemical or physical cues may be important to consider.

Davis, J.P., Barenburg, C. and Pederson, D. 2000. Burrowing response of juvenile geoducks (*Panope abrupta*) to changes in temperature and salinity. J. Shellfish Research 19: 689. (abstract). Burrowing behavior was examined in different size classes of juvenile geoducks in response to changes in temperature and salinity in the laboratory. Maximal burrowing response for all three size classes examined occurred at the intermediate temperatures tested (11, 14 and 17 °C) and higher salinities (26, 28 and 30 ppt). All burrowing responses (time of burial) increased as salinity conditions neared ambient (30-32 ppt). Salinities lower than 26 ppt and temperatures in excess of 23 °C showed significantly reduced burrowing response in all three size classes of geoduck examined. The research indicates that juvenile geoducks have limited tolerance for reduced salinity and high temperatures and may help to explain intertidal distribution patterns of this species in intertidal regions. Specific combinations of temperature and salinity may limit recruitment of clams into intertidal regions if physiological thresholds for these parameters are exceeded. The results also indicate that *P. abrupta* may be less tolerant of estuarine conditions than other native clams, a factor that could further help explain the distribution of this species in intertidal and subtidal habitats.

Goodwin, L. 1973. Effects of salinity and temperature on embryos of the geoduck clam (*Panope generosa* Gould). Proceedings of the National shellfisheries Association, Vol. 63: 93-95. Combined effects of salinity and temperature on embryogenesis in geoducks (fertilized egg through trochophore to prodissoconch I stage, or D-hinge larvae) were examined utilizing a matrix of salinity and temperature treatments. Optimal tolerance to salinities lower than ambient (30 ppt) was observed at rearing temperatures of 10 and 14 °C. Abnormal development was observed at salinities in excess of 32.5 ppt and less than 25 ppt at all temperatures examined. Rearing temperatures above 16 °C were unfavorable to development. The experiments suggested that geoduck embryos have relatively narrow temperature and salinity optima for normal embryogenesis. Of interest is the finding that larval development did not proceed normally at salinities typically observed in the ocean, suggesting early larval development may be favored in conditions more typical of estuaries. Developmental rate as a function of temperature was also observed in this study. At 6 °C, 96 hours was required for initial embryos to reach the D-hinge stage, whereas 60, 40 and 24 hours were required to reach the D-hinge stage at 10, 14 and 18 °C, respectively.

Goodwin, L. C. and B. Pease. 1989. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest) Pacific Geoduck Clam. Biological Report 82(11.120) US Fish and Wildlife Service, 14 pp. Physiological aspects of geoduck biology relating to gametogenesis, spawning and post settlement is described in some detail. Unpublished observations of Shaul are particularly interesting. He noted that clams from warmer water locations (South Sound) tended to spawn earlier in the year under laboratory conditions than did clams from regions having cooler ambient temperature regimes (e.g. Strait of Juan de Fuca). Female geoducks were observed to release an average of 1-2 million eggs per spawning event, with the largest release of eggs estimated at 20 million for a single individual. Information on the rate of larval development of geoducks maintained under different temperature and feeding regimes was provided for studies conducted at the Point Whitney Shellfish Laboratory (WDFW). The shortest larval development period observed was 16 days for larvae reared at 16 °C. The larval period lengthened to 30 days @ 17.6 °C to as long as 47 days @ 14 °C (from Goodwin et al. 1979). The onset of settlement (cessation of pelagic life and use of velum for locomotion in the water column) and metamorphosis (loss of velum, anatomical rearrangement of retractor musculature, ontogeny of ctenidial (gill) filaments and growth of siphon are crucial components in the life cycle of bivalve mollusks, including geoducks. This post-larval (dissoconch) stage is extremely critical and constitutes one of the major bottlenecks in the production of hatchery reared juveniles, and suggests that changes in water quality or other environmental parameters influence the physiology and subsequent behavior of juvenile geoducks at this life history stage. Shaul's unpublished observations are of particular importance here. Relatively minor changes in water chemistry, food availability, temperature, salinity and chemical or physical cues provided by adult geoducks or other infaunal animals may influence the migratory behavior and final settlement of dissoconch geoducks. Shaul noted that dissoconchs utilized a byssal production gland in the foot to attach to individual sand grains, thus anchoring the clam to the substrate. The use of sand anchors, however did not preclude the migration of clams as it was noted that clams could emerge from the substrate and utilize byssal threads as a sail to move clams in a down current direction. This capability was observed in clams as large as 5 mm, but was more prevalent in smaller clams. The important point made by Shaul that has implications for subsequent gene flow and population structure was that recently settled clams may have dispersal capabilities that are not generally appreciated. Of critical importance is the physiological interplay between salinity, temperature, food supply and other cues that structure post metamorphic behaviors in juvenile clams.

Goodwin, C. L. 1976. Observations on spawning and growth of sub-tidal geoducks (*Panope generosa*, Gould). Proc. National Shellfisheries Association, 65: 49-58. Report focuses on life history parameters of geoduck clams with references to physiological variables related to spawning cues and gametogenesis in geoducks collected from a wide variety of locations in Puget Sound and Hood Canal. Geoducks of both sexes are dribble spawners where spawning occurs at various

times during the spawning period, gradually evacuating the gonad of gametes, as opposed to one single event where the gonad is completely evacuated of eggs or sperm. Gametogenesis is initiated in the early fall, perhaps cued by decreasing water temperatures associated with autumn plankton blooms. Differences were observed in female and male geoducks with respect to body size for the onset and timing of gametogenesis. Female geoducks follow a more concise seasonal pattern of gametogenesis than did males. Female clams were observed to spawn in the spring with the largest shedding of ova occurring in April through June, with the greatest release of eggs in June. Clams were observed to be spent by July and active gametogenesis resuming in September. Active gametogenesis occurs through the fall months with animals capable of spawning by January, and clams fully ripe by March or April. Male clams followed a more variable pattern as sperm was observed in animals during all months of the year, however the majority of spawning occurred during the late spring (May and June) as in females. Physiological changes associated with glycogen storage in male and female geoducks were also noted as connective tissue in the gonad between adjacent follicles was thicker in the early fall during the onset of gametogenesis and gradually thinned as glycogen or lipid was converted into ova and spermatogonia. The physiology of spawning behaviors of clams held in the laboratory as it relates to water temperature was also investigated. In this case, it was observed that in over 35 separate trials, spawning occurred at temperatures between 8.5 – 16 °C, with the majority of spawning occurring at 12-14 °C. Rates of growth of subtidal geoducks were also measured in this report utilizing mark recapture methods for geoducks growing in five Puget Sound locations in both Hood Canal and northern and southern parts of Puget Sound. For Puget Sound as a whole, growth in geoducks is relatively rapid for the first ten years; as clams grew to an average of about 60mm after the first three years slowing to about 20 mm per year till the 6th year and slowing to about 10 mm per year to age ten. After 10 years, shell growth occurs very slowly. The generalized growth curve appears characterized by the von Bertalanffy model with an approximate asymptotic size of 145 mm reached after the 10th year. The relationship between live weight and age is also described, and appears to be characterized by a logistic model; geoducks on average for 5 Puget Sound locations attained a weight of 200 g after 3 years, 400 g after the 4th year, 600 g after the 5th year, and a marketable 800 g after the 6th year. A mean asymptotic weight of 1200 g after the 10th year was observed in this study. After 10 years, it was observed in this study that growth declined rapidly, as appears the case for geoducks generally. Clearly geoduck growth will vary significantly by locale (see also Breen and Shields, 1983 and Harbo et al., 1983).

Goodwin, C.L. and Pease, B.C. 1987. The distribution of geoduck (*Panope abrupta*) size, density and quality in relation to habitat characteristics such as geographic area, water depth, sediment type and associated flora and fauna in Puget Sound, Washington, Washington State Department of Fisheries, Technical Report 102, WDF, 44 pp. This technical report considers the size and distribution of geoduck resources in Puget sound and Hood Canal as a function of habitat geographic region, water depth and habitat qualities such as sediment type and associated plant and animals that co-occur with this species. From a physiological perspective, the often noted observation that geoducks collected from southern Puget Sound are on average larger than geoducks from the northern portions of the sound, and larger still than clams from Hood Canal is attributed to faster rates of growth (see Andersen, 1971; Goodwin, 1976; Breen and Shields, 1983; Goodwin and Shaul, 1984). Faster rates of growth in southern Puget Sound are generally attributed to warmer average seawater temperatures in the summer and higher local primary production spread out over the summer months coupled with generally high flushing due to strong tidal currents creating a high flux of available phytoplankton to benthic, suspension feeding clams, generally. Central Puget Sound and Hood Canal are characterized by shorter, more intense phytoplankton blooms in the spring and fall and relatively lower food availability due to a reduced flux of suspended food availability during the summer (even though seawater temperatures are generally warmer). These conditions contribute to a reduced annual rate of growth in the main basin and Hood Canal, respectively. That there is an observed latitudinal shift in smaller average geoduck size with increasing latitude in Puget Sound is likely a result mainly of geographical differences in productivity and food availability, and not to any genetic or other differences between geoducks. That average geoduck size in British Columbia is larger than that in Washington State reinforces the view that differences in average size are due to physiologically mediated differences in rate of growth that is largely a function of food availability, and to a lesser extent mean seawater temperature over an annual cycle. In fast growing areas in southern Puget Sound, geoducks averaged 30 mm per year for the first 3-4 years. WDF unpublished data reported here indicated that recorded growth in an individual geoduck averaged 5.7 mm per month, or nearly 67 mm annually, while average growth rates for hatchery produced seed planted in a productive southern Puget Sound habitat was 3.4mm per month. Clearly, rate of growth in geoducks will vary greatly by site and culture conditions as has been the case for cultured bivalves, generally.

Russell S. and Keeley, N. 1995. The geoduck clam (*Panopea generosa*) Malaspina University College, in conjunction with IEC and Fan Seafoods Ltd. research report, 49 pp. This white paper was written by undergraduate students at Malaspina College in 1994/1995 and includes original research on behavior and physiology of geoducks as it relates to feeding, burrowing and post planting dispersal under experimental conditions. Behavioral components related to post-settlement burrowing focus on the rocking motion commonly observed in clams during the burial process as the anterior pedal retractor muscle contracts prior to the posterior retractor, thus generating a burrowing motion (also observed in juvenile geoducks by King (1989)). Other observations included active protrusion of the siphon into the water column by juveniles during periods when suspended algae was available in the water column, and retraction of the siphon below the substrate level when food levels were low in the aquaria, or not available when the animals were disturbed (e.g. during water changes).