The Potential Impacts of the Commercial Geoduck (*Panope generosa*) Hydraulic Harvest Method on Organisms in the Sediment and at the Water-Sediment Interface in Puget Sound.

by

Georgina B. Willner

A Thesis: Essay of Distinction
Submitted in partial fulfillment
Of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
June 2006

This Thesis for the Master of Environmental Studies Degree

by

Georgina B. Willner

has been approved for

The Evergreen State College

by

Amy Cook
Member of the Faculty

Date

ABSTRACT

The Potential Impacts of the Commercial Geoduck (*Panope generosa*) Hydraulic Harvest Method on Organisms in the Sediment and at the Water-Sediment Interface in Puget Sound.

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An assessment of the potential impacts of the commercial geoduck harvest in Puget Sound on the structure and functions of infaunal communities as well as their habitats found that infauna provides a variety of important ecological functions that are critical in the uptake and recycling of nutrients and energy in aquatic ecosystems. Infauna continually mix and rework of the sediment in their mobility, feeding, burrowing, tube construction and irrigation activities in a process of sediment mixing called bioturbation. Bioturbation creates interstitial spaces and channels for oxygen and water flow; transfers nutrients across the sediment-water interface providing essential nutrients for primary production; increases water clarity; decreases the likihood of pollutants from being resuspended into the water and regulates the release or burial of cysts and eggs that may play a significant role in the stabilization of marine populations and community dynamics.

Geoducks are harvested throughout Puget Sound by scuba divers using a hand-held water jet that liquefies the sediments. Infauna are typically distributed to a depth of 15 centimeters, whereas, water jet harvesting can disturb sediments to a depth of 100 centimeters. Since the water jets disturb to a much greater depth than the infauna inhabit, all the infauna are impacted by the hole excavation. It is unlikely that any organisms escape impact.

Community composition and dynamics are changed by the commercial geoduck harvest. Organisms are crushed, buried, removed or resuspended causing high mortalities or relocation. Diversity and collaboration of functions that creates complex and productive communities are lost. Habitat that provides protection, nurseries, and food are destroyed.

Considering the role infaunal communities play in nutrient cycles, changes in functional diversity and functional composition of infaunal communities will predictably impact ecosystem processes. It is essential to recognize that the risks include many factors in addition to the direct effects on the commercially important species. Maintaining a stable ecological community is an important element to the sustainability of the fisheries as well as the well being of Puget Sound.

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Acknowledgements

I am exceptionally grateful to my husband, Brian Willner, for his support and patience. I am immeasurably indebted to Barbara Pacifico and Anna Crickmer for their support and guidance. I truly appreciate Senator Karen Fraser's time and guidance which I have found invaluable and insightful. I thank Professor Amy Cook, my thesis reader, for her guidance and input.

Professor Dave Milne and Professor Erik Thussen were instrumental in introducing me to marine biology and have inspired and challenged me. Dave Milne inspired me as an undergraduate to pursue the study of benthic organisms as a marine research project and taught me the power of investigation and simple theory.

I would like to thank the Dove chocolate factory for the constant supply of inspiration in the form of tasty bite-size chocolate morsels.

I. Introduction

The Washington State Legislature reviewed, in the 2006 Legislative session, a bill proposing to change commercial geoduck (*Panope generosa*) harvesting regulations. Legislative members weighed the economic benefits of increasing the area of harvestable commercial geoduck (the amount of geoduck biomass available for harvest) against the environmental impacts caused by commercial geoduck harvest. The regulation prior to the 2006 Legislative session prohibited commercial geoduck harvest in areas that are shallower than 5.5 meters below mean lower low water and within a line 183 meters seaward from and parallel to the line of ordinary high tide. The approved legislation allows commercial geoduck harvest in areas shoreward of 183 meters that are not shallower than 5.5 meters below mean lower low water (DNR, 2001).

Opening additional harvestable area increases the amount of geoduck biomass available for harvest, which will result in higher state revenues. While the economic benefits of this change make the proposed legislation appealing on the surface, the impact of this change on the natural environment, and the subsequent impact on the fishing industry as a whole in Puget Sound, may result in damages that will far exceed the immediate benefits.

The geoduck fishery is a $40 million-a-year industry providing food, employment, and international trade in addition to income for Washington State (The Associated Press, 2001). The geoduck fishery generated $60 million of revenue for the State over the past 10 years. The revenue is used by the State: to clean up contaminated sediment in Puget Sound; to inventory nearshore aquatic habitat; for geoduck fishery management and enforcement programs; for WDFW capital improvements and operations including shellfish programs; for State/Tribal shellfish negotiations; and for Aquatic Land Enhancement Account (ALEA) grants to local governments to purchase, develop and restore aquatic lands for public access and habitat restoration (DNR, 2001; DNR, 2002).

This paper examines and discusses the potential impacts of commercial geoduck harvest techniques on benthic infauna and benthic communities' structure and composition. The physical disturbance associated with the commercial geoduck harvest has the potential of altering the structure and dynamics of benthic communities as well as the availability and distribution of physical microhabitat and biogenic structures. Are benthic organisms critical to the ecology of Puget Sound? The environmental impacts of commercial geoduck harvest may be adversely affecting water quality, natural aquatic habitats, and other fisheries' success. Could the physical disturbance associated with the commercial geoduck harvest be linked to lowered water quality and nutrient loading in Puget Sound that is causing closures of shellfish growing areas due to high levels of nutrient and bacteriological pollution, low dissolved oxygen levels and fish kills?

The hydraulic harvest method of the commercial geoduck fishery has the potential to have a large impact on the infaunal habitat. Geoducks are commercially harvested using water pressure guns, projecting 18 to 27 kilograms of pressure per 2.5 centimeters square that liquefies sediment and dig 46 centimeter deep holes. Displaced materials are deposited in an area around the hole approximately 1.2 meters in diameter. One diver can harvest 800 clams per day or approximately 680 kilograms (DNR, 2001; Palazzi et al, 2001). There are usually two divers per harvest site per day – disturbing a total of 1463 square meters of substrate per day. The substrate is not only disturbed by the harvest with pressured water jets but also general diver activity and equipment dragging along the bottom creates physical disturbance to the habitat, which can alter the structure and dynamics of benthic biological communities (VanBlaricom, G.R. 2002).

Although the perception of the general public is that sub-tidal sediments are uninhabited or sustain little life, these sediments do in fact sustain complex and active populations that reside in and at the water-sediment interface. A large number of species of micro- (organisms that are smaller than 44 µm), meiso- (organisms that are 44 to 300 µm) and macroorganisms (organisms larger than 300 μm) live in and at the sediment-water interface (Currie et al, 1996; Snelgrove, 1999; Watling et al. 1998).

The commercial geoduck harvest could result in the release of eggs and cysts buried in the sediment, which may result in phytoplanktonic blooms including toxic algal blooms. A large influx of cysts or pathogens into the water system could have detrimental effects on the food web and cause shellfish fishery closures. Large phytoplankton blooms can result in conditions of low oxygen in the Sound and result in fish kills. Long-term costs to the environment should be weighed against the short-term benefit of the additional commercial geoduck harvest revenues.

Maintaining a stable ecological community is an important element to the sustainability of the geoduck fishery as well as other fisheries in the Puget Sound. The physical disturbance to habitat caused by harvesting with pressured water jets, diver activity and equipment dragging along the bottom has the potential of altering the structure and dynamics of benthic infaunal communities (VanBlaricom, G.R., 2002). Changes in the infaunal community structure and dynamics can affect the entire food web of the Puget Sound. Consideration should be given to benthic fauna and infauna communities that may be buried or changed in the process of commercial geoduck harvesting.

The thesis theorizes that the commercial geoduck harvest can crush, bury and expose benthic organisms to predation; alter sediment structures and water column biogeochemistry. This thesis will analyze whether or not there is a correlation between the infauna communities that may be disturbed by the commercial geoduck harvest and the water quality concerns of low oxygen, increased nutrient levels and increased occurrences of paralytic shellfish poisoning in Puget Sound. Studies regarding the effects of marine harvesting causing sediment disturbances on benthic organisms and their communities will be reviewed in order to understand how the removal of a predominant organism (the geoduck) and the disturbance of flow, nutrient and substrate related variables impacts benthic communities' dynamics.

II. Geoduck

A. Biology

Geoducks occur predominantly sub-tidally and intertidally in low numbers throughout Puget Sound (Bradbury et al, 2000). They prefer to live buried in sand or sand-mud substrates from the lower intertidal zone to depth of up to 109 meters below 0 tides. Geoduck larvae and juveniles initially reside at the sediment-water interface, and with increasing age and size, bury themselves deeper into the sediment (See Table 1) (DNR, 2001; Goodwin, 1987).

Age	Burrow as deep as	Burrow generally to depths of	Shell size	Weight
1 yr	30 cm	20 cm	3 cm long	10 gm
3 yr	65 cm	60 cm	10 cm long	300 gm
10 yr	80-90 cm (90 max)	80 cm	17 cm long	1600 gm

Table 1: Geoduck burrow depth, shell size and weight for age class. (Source: Goodwin, 1987).

Geoducks are extremely long-lived; the oldest known geoducks are 165 years old. As the largest bivalve in North America, geoducks are known to grow up to 6.5 kilograms; reaching full size in approximately 10 years (DNR, 2002). Much like old growth forests' aged trees, mature geoducks use resources for maintenance rather than growth (Anderson, 1971). Geoducks in prime habitat can reach market weight of 0.9 kilograms (2 pounds) in 4 to 5 years (Anderson, 1971; Bradbury et al, 2000; DNR, 2001; Goodwin, 1987).

Growth is dependent on water temperature, habitat/substrate suitability and food availability. Although geoducks can occur in mud or pea gravel-gravel substrates, in these locations, they have smaller shell sizes and are present in lower numbers than in sand or sand-mud substrates (DNR, 2001; Goodwin, 1987). Phytoplankton productivity in the locality and the volume of tidal currents are major factors of food available in the water column. In Puget Sound, mud substrates are more likely to be found as the water depth increases and the current become slower, because this allows deposition of fine materials. The slow current speeds in high deposition areas of fine sediments may not provide the food those areas of higher currents carry. Sand-mud substrates where geoducks are found in high abundances are areas of higher current speed. The highest abundances of geoduck are found at the intermediate water depths (between 5.5 meters and 20 meters below the lower low water line) (Goodwin, 1987).

Geoducks reach maturity between 3 and 5 years and typically spawn late winter to early summer (April to June) (DNR, 2002). Goodwin (1987) concluded from the low numbers of juveniles present that recruitment was a major limiting factor in many areas of Puget Sound. In addition to low recruitment that is typical of long lived organisms, geoduck eggs and larvae experience high mortality rates as a result of predation and poor water conditions. Juveniles experience greater mortality than most bivalve species because they are especially fragile due to their inability to retract their bodies into their shells for protection (Bradbury et al, 2000a; Goodwin et al, 1984; Dewey, 2006; Palazzi et al, 2001). They are easily smothered or crushed by movement of the substrate (Anderson, 1971).

In their first 2 years, juvenile geoducks live buried at shallow depths in the substrate and are susceptible to predation by foraging organisms that can dig down into the sediment. At high risk from predation by flatfish, shrimp, snails and starfish or being crushed merely by substrate movements, very few juvenile geoducks survive to a harvestable age (Bradbury, 1999 and 2000). Adult geoducks have a low rate of natural mortality, since they burrow to deeper depths with only their siphons exposed, predation is a minor threat. Siphon nipping is a minor cause of mortality (Bradbury et al, 2000a; Goodwin et al, 1984; Palazzi et al, 2001).

B. Fishery

The commercial geoduck fishery is the most valuable clam fishery on the west coast of North America. Geoducks were first commercially harvested in the Puget Sound in 1970, when the

Washington State legislature passed legislation requested by the Washington State Department of Fish and Wildlife (WDFW) and Washington State Department of Natural Resources (DNR) to open Puget Sound to commercial geoduck harvesting (Goodwin, 1987; Puget Sound Action Team, 2003). Prior to 1969, state law prohibited commercial geoduck harvesting. Landings grew from 37 metric tons the first year of harvest to 3,922 metric tons by 1977 and over fishing was feared by DNR and WDFW (see Table 2). In 1979, a harvest limitation of 2,350 metric tons reduced the catch. A maximum annual take level of 2,267 metric tons was set in 1987 (Goodwin, 1987).

C. Harvest

WDFW established 6 geoduck management regions within Puget Sound (See Figure 1, Washington State Commercial Geoduck Management Regions). Each region has several individual tracts (See Figure 2, Map of Identified Geoduck Tracks in Washington State) - the mean size of the 267 tracts, in 2000, was 43 hectares (Bradbury et al, 2000). Tract boundaries can be changed to fit management needs (Bradbury et al, 2000). Tracts are designated commercial or non-commercial depending on water depth, pollution levels, density of geoducks, quality of product, harvesting difficulty or conflicts with endangered species (Callahan, 2003). Densities

Year	Pounds	Metric Tons
1970	82,000	37
1971	610,000	277
1972	493,000	234
1973	464,000	210
1974	803,000	364
1975	2,373,000	1,076
1976	5,366,000	2,434
1977	8,647,000	3,922
1978	7,090,000	3,216
1979	5,228,000	2,371
1980	3,910,000	1,774
1981	4,290,000	1,946
1982	5,303,000	2,405
1983	3,523,000	1,1598
1984	4,421,000	2,005
1985	4,109,000	1,864
1986	2,602,000	1,180

Table 2. Puget Sound Commercial Geoduck Landings (whole wet weight). (Source: Goodwin, 1987).

vary significantly between the five regions of Puget Sound. The density of geoduck in tracts that are leased for commercial fishing ranged from 0.3 to 4.9 geoduck/ meter^2 which is in the lower part of the range for all areas of 0 to 22.5 geoduck/ meter^2 (Goodwin, 1987).

In order to prevent damage to the geoduck habitat and to conserve the resource, the Legislature directed that harvesting is to be done using manually operated, hand-held water jets or suction devices that are controlled by a diver and not by someone above the water (RCW 77.60.070). Water is injected under pressure next to a geoduck siphon in order to liquefy the sediment and enable the diver to reach down and remove the geoduck. This method of harvesting is considered to be the most environmentally benign method available (Palazzi et al, 2001).

Each hole created by the hand-held water jet is roughly 38 centimeters in diameter and 46 centimeters deep immediately after digging. Approximately 20 kilograms of material are displaced into a berm around the hole. Depending on the current in the area, the displaced material can settle up to 1.5 meters down current from the harvest hole. In weaker currents, the diameter of the berm plus

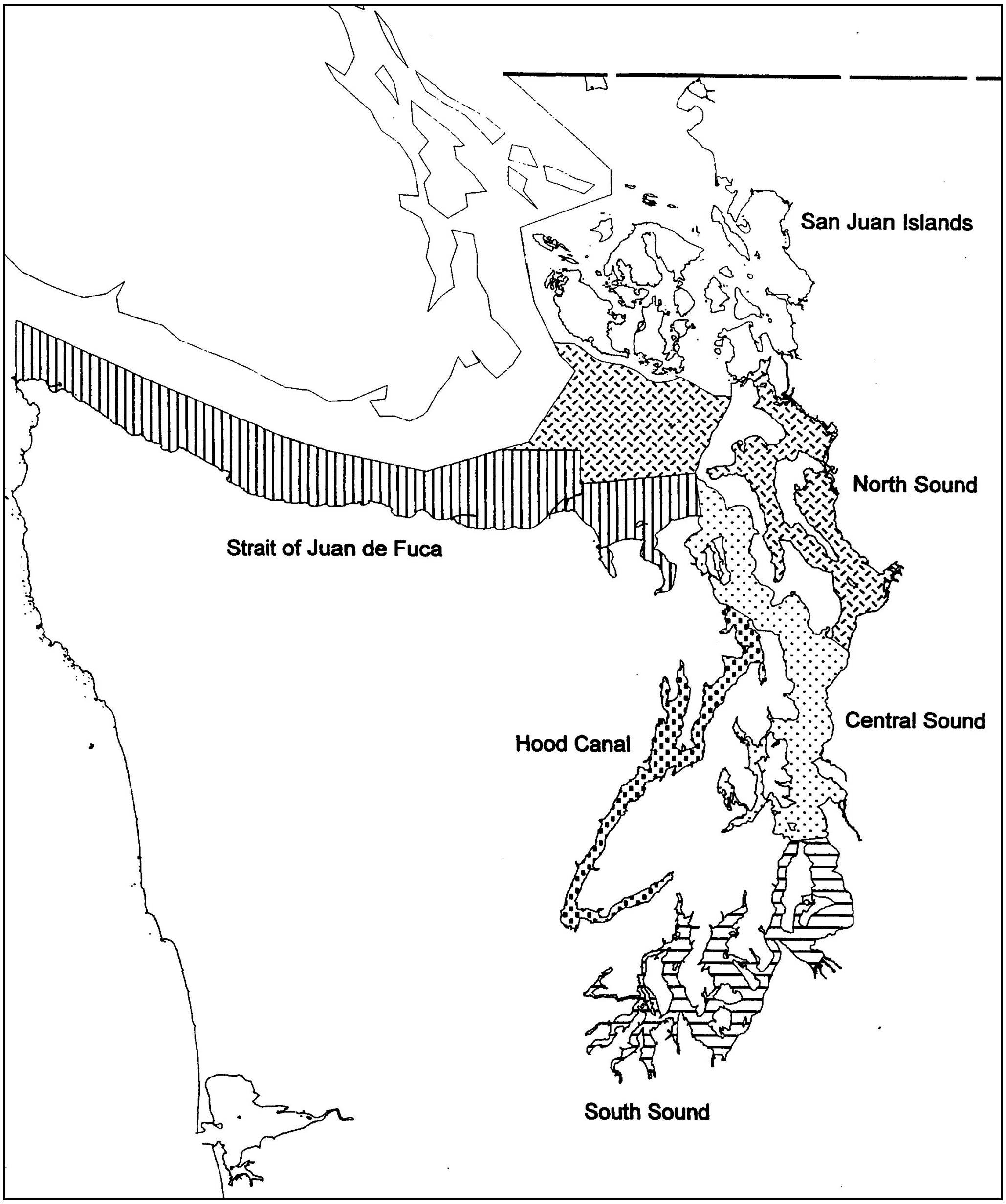

Figure 1: **Washington State Commercial Geoduck Harvest Management Regions.** (Source: Palazzi et al, 2001)

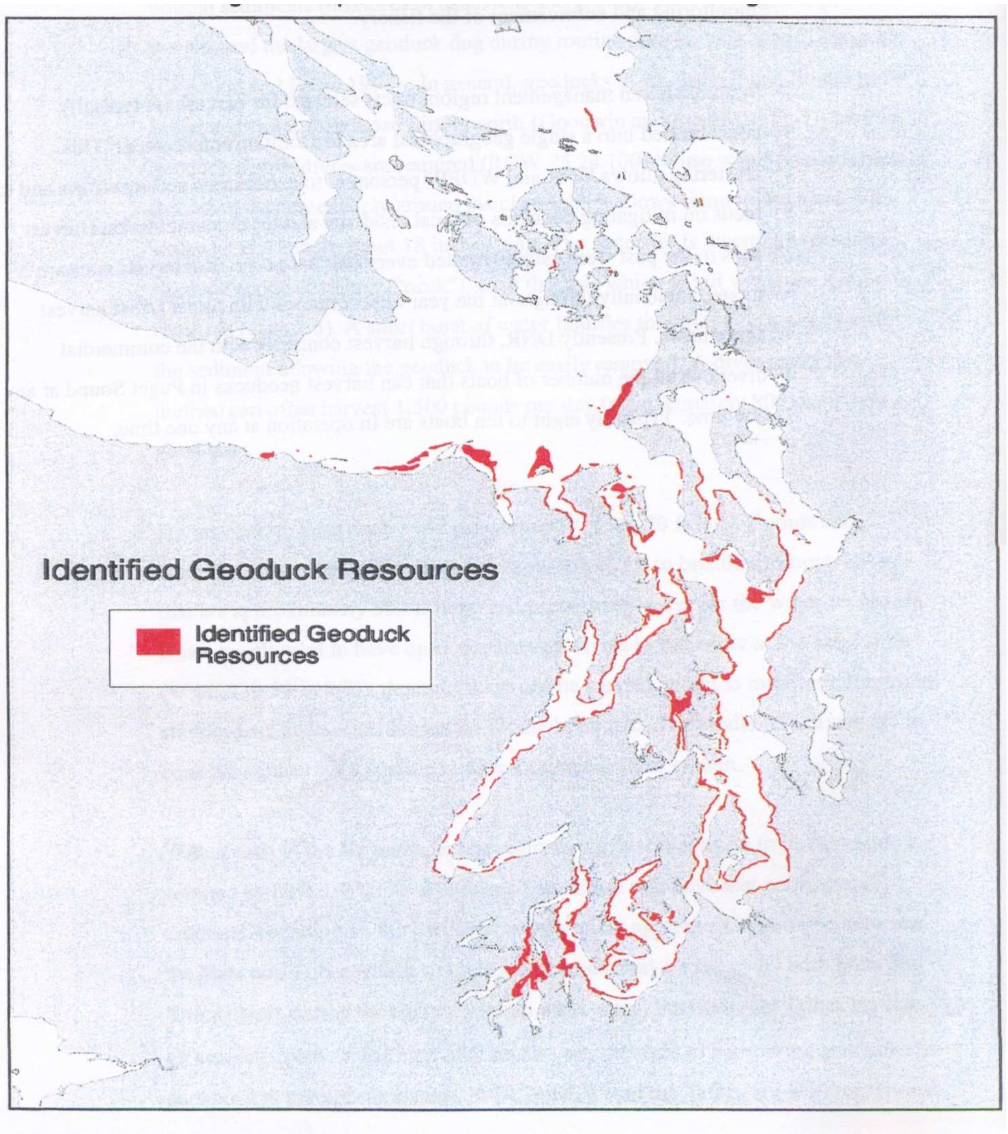

Figure 2: **Map of Identified Geoduck Tracts in Washington State**.
(Source: Palazzi et al, 2001)

the hole is about 1.2 meters with a total disturbed area of about 1 square meter (DNR, 2001; Palazzi et al, 2001). This does not include the area disturbed by diver activity. The area within a geoduck tract that is actually dug depends on the resource density.

The commercial geoduck harvest can take 4,050 clams per hectare annually on an average commercial tract. A hectare is approximately 10,000 square meters, therefore, ½ of the area could potentially be disturbed by the harvest. However, the Final Supplemental Environmental Impact Statement (SEIS) (2001) reports that a liberal estimate of the area affected by digging is 25% of the area of a tract (Palazzi et al, 2001).

Each harvesting vessel is limited to a maximum of 2 divers in the water at any one time (Callahan, 2003). One diver can generally harvest 680 kilograms per day which equates to approximately 800 clams. Taking 800 clams disturbs 488 square meters per day not including diver activity (Palazzi et al, 2001). One commercial geoduck harvesting boat with two divers disturbs almost ½ of a hectare within 10 days of harvesting.

Harvest is prohibited in waters shallower than 5.5 meters and deeper than 21 meters (Callahan, 2003). The 21 meter boundary is the limit at which divers can safely operate without decompression. The shoreward boundary protects sensitive nearshore habitat, plants and organisms (Palazzi et al, 2001).

The total biomass of the geoduck population in Puget Sound is estimated at 306 million kilograms with approximately one quarter or 74 million kilograms within the commercial harvest tracts (DNR, 2002; Puget Sound Action Team, 2003). The average density of geoduck in unfished tracts is 5.5 geoduck per square meter which equates to 2,785 geoduck per hectare. An average of 72% of the geoduck biomass is removed from a tract which means approximately 2,025 holes on average per hectare (Palazzi et al, 2001)

WDFW calculates, from biological stock assessments, a Total Allowable Catch (TAC) for each tract which signifies the cumulative weight of geoduck that can be removed without affecting the sustainability of the resource. Sustainable yields are estimated using estimated growth rates, mortality and recruitment rates of the total geoduck population. The annual TAC is 2.7% of the total estimated commercially available geoduck biomass (Bradbury et al, 2000; Callahan, 2003; Palazzi et al, 2001). The entire regional TAC is harvested in a limited number of tracts each year and the fished tracts are not to be harvested again until the resource has returned to its original density and biomass (Goodwin and Bradbury, 2000).

Recovery of a geoduck population is slow for two primary reasons: 1) geoducks have a low rate of recruitment; and 2) geoduck eggs, larvae and post-settled juveniles have a high mortality rate. Using data from studies of geoduck tracts in Puget Sound, the average recovery time for a harvested geoduck population is predicted to be 39 years (Palazzi et al, 2001).

Goodwin and Bradbury (2000) reported that in a study of 15 fished tracts, geoduck densities were decreased on average by 72% with a range of 19% to 95%. The decreases in 14 of the 15 tracts were statistically significant.

III. Soft Sediment Ecology

A. Abiotic Conditions

Sediment composition and structure are critical elements determining the richness and diversity of a benthic community. Sediment stability, grain size and distribution, and the ocean floor structure are important habitat criteria for organisms. Sediment structure affects the hydrodynamics along the ocean floor which impacts the deposition of organic material. Organic matter content, and mineral and chemical compositions within the sediment provide essential life-sustaining nutrients and oxygen. The concentration of organic material will be proportionate to the productivity of the area (Goodwin, 1987, Probert, 1984; Rhoads, 1974).

Sediment stability is important to the development and stability of a diverse benthic community. The degree of sediment stability is relative to the interparticle adhesion, grain-size distribution, water content and bed roughness, which are all directly influenced by the benthic community (Probert, 1984). Sediment stability is an important factor in the degree that a sediment surface is susceptible to erosion and the impact of sediment surface erosion has on turbidity, nutrient content, and benthic structure.

B. The Influence of Organisms on the Sediment Ecosystems

2. Organisms as Habitat Engineers

The benthic organisms' activities and interrelationships are critical to the biological, chemical and physical properties of the sediment (Probert, 1984). Bioturbation, the reworking of sediment by organisms that live in and on the sediment, is an important factor influencing the sediment structure and composition and is an essential element of the food web. Bioturbation increases the depth of the sediment aerobic habitat, the area available for microorganism colonization (Probert, 1984). Organisms rework the sediment through feeding, burrowing or tube construction and mobility activities (see Figure 3: Methods of mixing and recycling of sediments by benthic organisms). These activities contribute to the regulation of carbon, nitrogen and sulfur cycling, sediment transport and stability, pollution distribution, dormant egg and cysted individuals' reintroduction into the water column, and secondary production (Snelgrove et al, 1997). Benthic decomposition and remineralization processes predominantly occur within the bioturbated zone of the sediments. Through bioturbation, organic and inorganic materials that are remineralized by infauna and the dissolved nutrients are released back into the water column, fueling primary production in the marine waters (Aller, 1994; Austen, et al, 2002).

Bioturbation positively affects the functioning, and stability of communities, which translates to benefiting ecosystem functioning as a whole. Burrowing populations play a significant role in channeling food particles and oxygen to infauna production including bacterial and enables the mineralization and nutrient release from the sediments to benefit the pelagic system. In addition, burrowing populations can oxygenate the sediments and prevent anoxia that may devastate the community during periods of eutrophication and high levels of organic matter deposition. (de Wilde, 1991)

Water content in the sediment is increased by bioturbation to greater than 60% (Hall, 1994). The increased water content in the sediment affects the amount of production and activity by increasing the depth of oxidization. Oxygen in the sediment fuels a variety of processes including sulfide and metal oxidation, nitrification and aerobic respiration. As the sediments are oxidized, aerobic colonization is promoted as the environment of the sediment become more tolerable to organisms. As organisms abundances increases, bioturbation increases, resulting in greater sediment stability, increased grain size and more interstitial spaces (porosity). (Rhoads, 1974; Snelgrove, 1997)

All benthic size groups of organisms play important roles in the stability of the sediments. Benthic organisms excrete previously ingested material as fecal pellets. Modal grain size and sediment porosity is increased by pelletization and by the secretion of mucopolysaccharides, which coat pellets

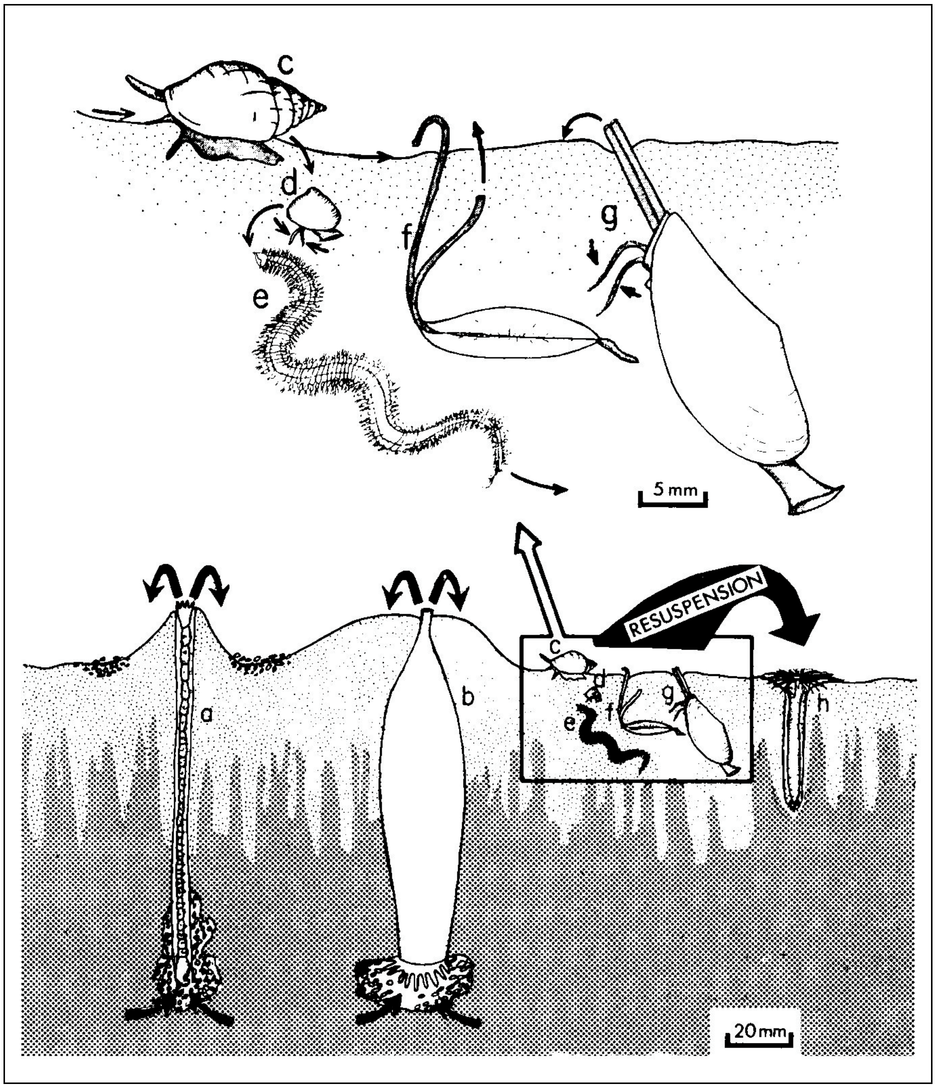

Figure 3: Methods of mixing and recycling of sediments by benthic organisms: a – maldanid polychaete; b – holothurian; c – gastropod; d – nuculid bivalve; e – errant polychaete; f – tellinid bivalve; g – nuculanid bivalve; h – anemone. Species a and b are conveyor-belt species which pump reduced sediments up to the oxidized surface. Species c, d, e, f and g rework sediments within the water-sediment interface. Direction of sediment ingestion and egestion of fecal matter is shown by the arrows. Species h, a suspension feeder, utilizes resuspended fecal pellets. (Source: Rhoads, 1974).

and particles and bind them to one another. Increasing sediment grain size through pelletization increases sediment stability and prevents erosion (Rhoads, 1982). The microbial populations live on particles, including fecal pellets, and within the interstices of the particles in the sediment. The accumulation of mucilaginous materials produced by microorganisms increases the adhesion between particles and alters the granulometry of the sediment. For example, the production of mucus by benthic diatoms binds fine sediments around them and algal mats are formed stabilizing the sediments and preventing erosion (Probert, 1984; Rhoads, 1982).

Many infaunal species utilize mucus that results in binding sediment particles and increasing sediment stability in a variety of manners. Some species use mucus excretions to form traps to capture food, for locomotion, protection, to adhere or anchor to sediment particles. Nematodes secrete mucus that forms agglutinations of sediment theoretically to capture detritus particles, bacteria and macromolecules. In addition, nemotodes establish complex networks of tightly-spaced, threadlike burrows that adhere sediments together (Probert, 1984). Macrofauna tube building is believed to stabilize sediments; however, more importantly, tube irrigation may promote microbial growth. Microbial activity produces mucilaginous material which increases sediment stability (Probert, 1984). The increase of sediment stability and the microbial community enhances meio- and macrofaunal abundances by providing suitable habitat and food resources (Luckenbach, 1986).

2. Nutrient Cycling

The marine benthos are teaming with tremendous biodiversity that provides a variety of important ecological functions. Organisms have critical roles in the uptake and recycling of nutrients and energy in aquatic ecosystems. Sedimentary fauna play important roles in global geochemical cycles -- carbon, sulfur and nitrogen cycles; secondary production; metabolic breakdown and burial of pollutants; and filtration of water at the sediment-water interface. The mixing, burrowing, feeding and locomotory activities of benthic organisms can modify the chemical, biological and physical properties of sediments. Bioturbation creates new pore spaces and channels for oxygen, nutrients and water flow providing new habitable areas for colonization by microbial communities. Microbial communities play important roles in decomposition and remineralization of organic material (Snelgrove, 1999; Wall et al, 1998).

Benthic organisms have an important role in secondary production. Very small microorganism (smaller than 44 μm) including bacteria, protozoa and fungi are decomposers of particulate organic carbon, making nutrients available for primary production within the sediment and in the water column. Microbial organisms are an important food source for meiofauna (includes nematodes and copepods) which also consume microalgae and organic particles. Macro- and meiofauna can be major dietary components of commercial species such as fish, crab and shrimp (Snelgrove, 1999). Each trophic group is an important link in the food web involving complex interactions with other links (Thrush et al, 2002).

Macrofauna play an important role in the cycling of carbon. Most sedimentary organisms are dependent on the sinking organic material produced in the water column which is primarily phytoplankton as a food source. Benthic decomposition and bioturbation are important in the transfer of nutrients back into the water column which enables the phytoplankton blooms. The decomposition of organic matter releases nutrients such as ammonia and nitrates that may be utilized by primary producers such as phytoplankton. Some carbon (organic material) is removed from the system through burial and is not decomposed and recycled (Snelgrove, 1997).

The transport of particles, contaminants, eggs and cysts, nutrients and oxygen are regulated by the marine benthic organisms. The release or burial of cysts and eggs by the sediment reworking activities of the infauna may play a vital role in the stabilization of marine populations and community dynamics and ensuring long-term persistence of the marine ecosystem (Anderson, 1997; Raffaelli et al, 2003).

Benthic organisms’ reworking activities impact the distribution and burial of pollutants. Organisms can decrease the likelihood of pollutants being resuspended by bioaccumulating or by binding pollutants to other particles through pelletization or mucous secretions. Many benthic microbes are able to decompose pollutants into organic compounds (Rhoads, 1982).

Suspension-feeders contribute significantly to water clarity and the reduction of nutrient levels through their filter feeding activities. Depending on species and size, bivalves can filter seawater at rates between 23 to 208 liters per day and remove approximately 17 grams of nitrogen for every kilogram of shellfish meat (Puget Sound Action Team, 2003).

3. Shell Material Contributes to Habitat Structure

Shell material from discarded, crushed, killed or previously dead organisms contributes to habitat heterogeneity by creating structures on the sediment floor and can armor sediments against erosion. Benthic biodiversity is positively correlated with habitat structure (Thrush et al, 2001). Shell material provides settlement surfaces for plants and organisms which through their settling activities bind sediment materials together to further stabilize the sediment and form structures (Hewitt et al, 2005).

C. Trophic Ecology of Soft Sediments

Marine benthic organisms fall into several trophic groups including: 1) deposit feeders, 2) suspension feeders, 3) herbivores, 4) carnivore-scavengers and parasites. Studies have shown that benthic communities are typically mixed communities of deposit- and suspension-feeders being the primary trophic types (Gray, 1974; Probert. 1984).

1. Deposit feeders consume organic detritus; mineral grains that may have bacteria attached; dissolved nutrients; and meiofauna and microfauna residing in the pore water or on sediment particles. Deposit feeders may feed at the surface or at depth within the sediment (Rhoads, 1974). Infaunal tubes and burrows increase solute flux across the sediment-water interface by increasing the sediment surface and inducing hydrodynamics across the sediment-water interface. The solute exchange across the sediment-water interface through tubes and burrows and infaunal activities controls oxygen penetration into the sediments which impacts the carbon, nitrogen and sulfur cycles by affecting microbial colonization, distribution, activity and processes (Rhoads, 1974, Snelgrove, 1997).

    2. Suspension-feeders capture suspended seston, which is composed of organic and inorganic particles using specialized body parts such as ciliated tentacles, mucus nets or ciliated or mucus covered

respiratory surfaces (Rhoads, 1974). Suspension feeders improve water clarity by removing particles from the water column, control phytoplankton populations through consumption, reduce the level of nutrients in the water column, and thus, allow more light to penetrate promoting the growth of benthic vegetation (Puget Sound Action Team, 2003). Depending on species and size, bivalves can filter seawater at rates between 23 to 208 liters per day (Puget Sound Action Team, 2003). A dense population of suspension feeders can effectively clean the water column by removing a large amount of suspended seston (Rhoads, 1974).

3. Herbivores consume plant material.

4. Carnivore-scavengers and parasites consume recently dead or living animal tissue.

D. Disturbance and Community Stability

Studies by Dr. David Tilman at the Cedar Creek Long Term Ecology Research Site, University of Minnesota show that communities with high diversity are able to withstand disturbance and invasion better than communities of lower diversity. In addition, diverse communities are able to recover from disturbances at faster rates. Dr. Tilman’s studies support the theory of mutualism which predicts that communities with a high degree of similarity do not sustain the community as efficiently as heterogeneous communities. Diverse communities utilize available resources more efficiently and are more productive at providing nourishment for the community, which enhances community stability and development (Barker 2000; Fargione et al, 2005; Tilman et al, 2001; Tilman et al, 1997). Species diversity, functional diversity and functional composition are primary contributors to efficiency, productivity and ecosystem processes (Tilman et al, 1997). The number of biotic interactions in a community is positively related to the complexity and organization of the community (de Wilde, 1991). Interactions between species create habitat conditions that are attractive and beneficial to other species. As an example, a shellfish bed provides three-dimensional habitat structures where other organisms may find shelter and food (Puget Sound Action Team, 2003). Complementarity affects of the functional differences of species in temporal and spatial resource and habitat use, and their positive interrelations, increase the efficiency and productivity of a diverse community (Tilman, 2001; Tilman, 2005).

Collaboration of functions amongst organisms creates higher community production and increases community complexity (Barker, 2001). For example, meiofauna and macrofauna provide the oxygen necessary to form the stability and development of microbial communities through tube irrigation and sediment reworking. Even a minor flow change at the sediment-water interface, such as the construction of a tube, can result in an increase in oxygenation and bacterial colonization (de Wilde, 1991). Predictability and ecosystem stability are important factors in the continuing development of a community's complexity and diversity (de Wilde, 1991). A disturbance, such as the commercial geoduck harvest, could disrupt the community's collaboration of functions by causing changes in the hydrodynamics, sediment stability and composition and food supply (Aller, 1982; Snelgrove, 1997).

Disturbances cause change or destruction of habitat structures, change of communities' resource base and/or are events that initiate species populational changes due to mortalities or removal (Probert, 1984). Marine plants which are generally limited to the shoreward boundaries of the commercial geoduck fishery tracts can be disturbed, damaged or removed (Palazzi et al, 2001). The physical disturbance associated with the geoduck fishery includes the impacts of local liquefaction, equipment dragging and general diver activity.

IV. The Geoduck Bed Community

Even though abundances and diversity between geoduck tracts differ, representation of groups is similar. Geoduck clams in many parts of Puget Sound dominate the infaunal biomass (Cain, 1996). Polychaete tube worms that form dense tube mats are abundant and widespread in geoduck tracts. Tube mats may serve as spawning substrate for organisms including herring (Palazzi et al, 2001).

Goodwin (1987) found 40 taxa of flora and macrofauna (focusing on epibenthic) commonly associated with high geoduck density. The five most common are chaetopterid polychaetes, sea cucumbers, sea pens, laminarian kelp and horse clams. Other common invertebrates included molluscs, crustaceans, echinoderms and cnidarians. The definitive explanation for the positive correlations was not provided by Goodwin and Pease, however, they hypothesized that some positive correlations were coincidental as organisms may prefer the same habitats or food sources. Studies have found that geoducks show a strong positive correlation with the presence of polychaete worm tubes. This is thought to be because the tube mats provide habitat that increases the geoduck larval metamorphosis and juvenile survival.

V. The Impact of the Commercial Geoduck Harvest

D. Sediment Structure

Disturbances, such as geoduck harvesting, homogenizes the area by breaking up structures and disturbing materials more evenly, reducing the structural complexity of the area (Hewitt et al, 2005). Bill Dewey, Taylor Shellfish Farms, (2006) has observed that adding structure to the ocean floor, such as PVC tubing for geoduck seeding, increases diversity, the richness and abundance of plants and fauna in and around the structures. Habitat structure provides protection, nurseries, and food sources (Dewey, 2006; Thrush et al, 2001). Hewitt, et al (2005) found that 18 more taxa were observed in patches of shell debris than outside of the patches. Structures on the ocean floor cause changes in the hydrodynamics around them which enhances local enrichment by increasing the deposition of particles.

As the water jet overturns sediments, organic material and organisms in and adjacent to the harvesting hole are resuspended and/or buried. The majority of the ocean floor including Puget Sound contains fine-grained deposits of silt and/or clay particles and organic detritus (Rhoads, 1974). Large sediment particles that are resuspended may have sinking rates of 105 centimeters/second with a probability of settling rapidly within the area that is disturbed, whereas, clay and fine particles resuspended at the same time settle at a slower rate and remain longer in the water column, and therefore, may be carried away from the area (Pilskaln et al, 1998). With larger particles settling quickly and finer materials being carried away, the result is a larger sediment grain composition with a lower concentration of nutrients, which affects the diversity of the species that will recolonize the area (Rhoads, 1974).

The resuspended sediment settles in an unconsolidated form and is susceptible to resuspension and erosion by currents and waves. The State of Washington Commercial Geoduck Fishery Supplemental Environmental Impact Statement (Palazzi et al, 2001) reported that the silt and clay content of undisturbed substrate averaged 3.5%, whereas the average found in the immediate harvested area is 2.3% (Palazzi et al, 2001). Goodwin (1978) studies also indicated that fine sediments were lost during commercial geoduck harvesting; resuspension of the sediments caused changes in the sediment grain size distribution.

Normally, the steady mechanisms of benthos processes release remineralized nutrients in the water column slowly over time (Pilskaln et al, 1998) resulting in a balance to the ecosystem. The water jet harvesting causes the sediment to lose adhesiveness by breaking the mucilaginous bonds between particles making the sediment more susceptible to erosion and resuspension, which increases turbidity in the water column and the release of nutrient. Resuspension of 1 millimeter of surface sediments may potentially double the nutrient flux into the water column from the sediment (Pilskaln et al, 1998). A large pulse of nutrients could increase the rate and influence the type of primary production. A large phytoplankton bloom would increase the amount of detritus flux and the rate of decomposition at the sediment water-interface, which increases the risk of anoxic conditions.

SEIS (2001) reported that the sediment plume within 5 meters of the harvest activity was dense, at 100 milligrams/liter above the background measurements. Depending on the species, different levels of water turbidity can adversely affect the growth or mortality of eggs, larvae and adults. Organisms vary in their sensitivity to turbidity and burial by silt. Some have no tolerance to burial. Eggs, juveniles and adults within a species can have different tolerances to turbidity. SEIS (2001) reported that bivalve larvae, for example, are more tolerant of turbidity than bivalve eggs, juveniles or adults.

Benthic organisms are typically distributed down to a depth of 15 centimeters (Probert, 1984), whereas, the commercial geoduck harvest excavates to depths of approximately 40 centimeters (Palazzi et al, 2001). The overturning of anaerobic sediments from below the oxidized top layer into the aerobic sediment water interface can have detrimental impacts on organisms that are intolerant of anaerobic conditions. Many organisms buried in anaerobic sediments cannot survive. Other organisms can overcome periods of low oxygen by lowering their metabolisms, switching to anaerobic glycolysis, or utilizing blood pigments as an oxygen reservoir (Rhoads, 1974). Some organisms have the ability to move to the surface and irrigate their burrows. However, an organism's ability to withstand periods of anoxia depends on the depth of burial under anaerobic sediments. This is probably not a concern since the hand-held water jets used to harvest the geoducks injects well-oxygenated water into the substrate which oxygenates the substrates within the harvest holes, and therefore, the benthic organism probably are not buried by anoxic sediments blown from the harvest holes.

E. Community Structure

The focus of this review has been primarily on infauna including those that are not readily apparent to the naked eye. Studies reviewed for this paper regarding the commercial geoduck harvest have not included examination of micro- or meio-organisms, but focused on larger macro-organisms. Community structure and dynamics can be changed by the commercial geoduck harvest; however, the changes and the impacts of the changes are largely unknown. The change may be in the successional progression to a stable community; allowing a foothold for a keystone species; changes in food resources; or changes in sediment composition. Goodwin (1978) measured total infaunal biomass of harvested tracts 7 months and one year after the geoduck harvesting and compared results to unfished tracts. Goodwin did not find statistically significant differences on 1mm mesh experiments. Total biomass captured on 6.35 mm mesh increased significantly after 7 months compared to unfished plots. They found individual species populations changed, increased or decreased, in one or two plots of six or seven tracts (Palazzi et al, 2001). The results show that community dynamics can be changed by the commercial geoduck harvest.

Benthic and pelagic systems are coupled in that benthic processes and patterns are likely to affect pelagic processes and patterns (Raffaelli et al, 2003). Removal of geoduck along with the incidental removal of other filter feeders may cause changes in ecosystem feeding patterns. Decreases in water filtration by the removal of filter feeders may cause an increase in phytoplankton levels and particles of high nutrient value in the water column. With the increased availability of food other species' populations may increase (Palazzi et al, 2001; Thrush et al, 20002). Zooplankton may increase with the increase of phytoplankton and in turn provide an increase in food sources available to fish (Palazzi et al, 2001). The long term effects of changes in trophic flow on the ecosystem as a whole are largely unknown. Two examples of this change in trophic structure are the dramatic reduction of cod, flounder and haddock which resulted in increased numbers of sharks and rays off the east coast of North America and a subsequent change in trophic flow since predators of cod, flounder and haddock do not typically prey on sharks and rays, these predators lost a critical food source (Austen, et al, 2002). Also, off the east coast, over-fishing of cod coincided with a dramatic increase in shrimp and crab populations (Austen, et al, 2002). The direct and indirect consequences of trophic flow changes are not fully understood. Changes in the diversity of the benthic community may cause an unforeseen ripple effect through the food web. Increases in phytoplankton and zooplankton may increase the amount of detritus accumulating on the bottom which will increase the microbial community resulting in reduction of oxygen levels in the water column.

Commercial geoduck harvesting disrupts the interactions of functions between species by crushing, burying, removing and resuspending organism causing high mortalities or relocation of the organisms to another area. Without the collaboration of functions the community dynamics collapse and the functions critical to the survival of the majority of the organism are lost. The disruption of the community destroys the mutualism of the organisms in habitat structure formation, sediment mixing and irrigation which are necessary to the availability of oxygen and nutrients. As discussed in Section III, D, changes in bioturbation can impact the porosity of the sediment and the flow of water.

Remove some of the infauna and sufficient functional redundancy may exist that the ecosystem can continue to function unchanged. However, removal of a species that has disportionate influence relative to other species (a keystone species) may result in major impacts to the carbon, nitrogen and/or sulfur cycles. Even though all species are probably not essential, their linkages to other species may be important to the community composition (Snelgrove, 1997). Infaunal community may have an abundance of weak functional interactions that stabilize the population size and dynamics (McCann et al, 1998). As a rule, only a very few (and possibly only one) functional groups in any community are keystone functional groups whose populations support or rework the ecosystem's primary vegetation pattern (Khanina, 1998). In this case, the infauna that bioturbate increase water content, and thus, oxygen in the sediment which gives rise to microbial communities. Microbial decomposers replenish the nutrients that fuel primary production and without the nutrients all other species cannot survive.

F. Mortality, Recovery and Succession

The largest abundances of benthic organisms occur in the top 2 centimeters of the oxidized layer; however, organisms are typically distributed to a depth of 15 centimeters (Currie et al, 1996; Probert, 1984). The hand-held water jet guns used to liquefy the sediment to remove geoducks disturb sediments to a depth of 46 centimeters and the organisms residing in the area are damaged, buried, relocated, resuspended or exposed to predation. Studies have shown that organisms can be reduced by 10 to 65% in sediments that are disturbed by commercial harvest of finfish and scallops (Currie et al, 1996; Dayton et al, 1995).

Many subtidal communities that are less prone to disturbances have fewer mobile species; therefore, mortality rates are higher. Patches resulting from natural disturbances of foraging organisms such as fish and crab are small scale in comparison to commercial geoduck harvesting impacts and can cause changes in community structure (Hall, 1994). The larger the disturbance the more impact there is on community resilience. Benthic communities that are subtidal and not exposed to frequent perturbations are more sensitive to disturbances than intertidal communities accustom to tidal or storm scouring and wave action. These communities probably contain species that are less mobile and less able to survive a harvesting disturbance (Dernie et al, 2003). Therefore, the original community members are less resilient to disturbance and are unlikely to remain after the disturbance.

The holes created by the hand-held water jets have been found to refill within 9 days to 7 months (Palazzi et al, 2001). Studies have shown that the fine particulate component of the sediment may be reduced and a large amount of shell fragments are exposed. Shell material from discarded, crushed or killed organisms creates habitat structures on the sediment floor and can armor sediments against erosion (Palazzi et al, 2001), and therefore, may be beneficial in the recovery of the harvested area.

Dernie et al (2003) found that benthic communities recover from low intensity sediment disturbances of depths of 10 centimeters occurred within 64 days, whereas, disturbances of depths of 20 centimeters occurred within 208 days. Post harvest surveys of the fished geoduck tracts assessed the time it takes for the geoduck extraction holes to refill, but the studies did not assess infaunal community recovery time. Recovery of a disturbed patch is successional. It is understandable that first the sediment surface and habitat needs to recover to a degree. Harvesting causes changes to the topography and alters the near bed hydrodynamics which affects the deposition of particles including organisms as well as organic material (Martin et al, 2005; Rhoads, 1982; Sherk, 1972; Thrush et al, 2001).

In disturbed areas, scavengers and predators quickly aggregate in inflated densities to consume exposed and damaged organisms. The scavengers and predators may hold a competitive advantage for the space until this food supply diminishes (Dayton et al, 1995) and then move to forage elsewhere.

The first organisms to colonize newly disturbed areas are small opportunistic tube dwelling polychaetes (see Figure 4). Tubicolous amphipods appear shortly after (Rhoads, 1982). Most pioneering species feed near the surface or from the water column. Living near the sediment-water interface, pioneering species are not efficient at mixing and reworking sediment, and therefore, the sediment water content can decrease significantly. Reduced compounds may be present in high concentrations in the pore water since eary successional species do little to regulate the chemistry of the sediment. To be able to maintain constant and low concentrations of solutes within their tubes using irrigation, pioneering organisms closely-space their tubes with small diameters; (Aller, 1982; Rhoads, 1982) and commonly form dense aggregations of tubes very quickly. The small space between the tubes in dense aggregations assists in controlling solutes within the tubes and reduces irrigation requirements. A greater nitrate flux out of the sediment may occur from the small numerous burrows than from the larger less numerous burrows of late successional assemblages (Pilskaln et al, 1998). As well, closely spacing tubes may have the additional benefit of creating sediment stability (Aller, 1982).

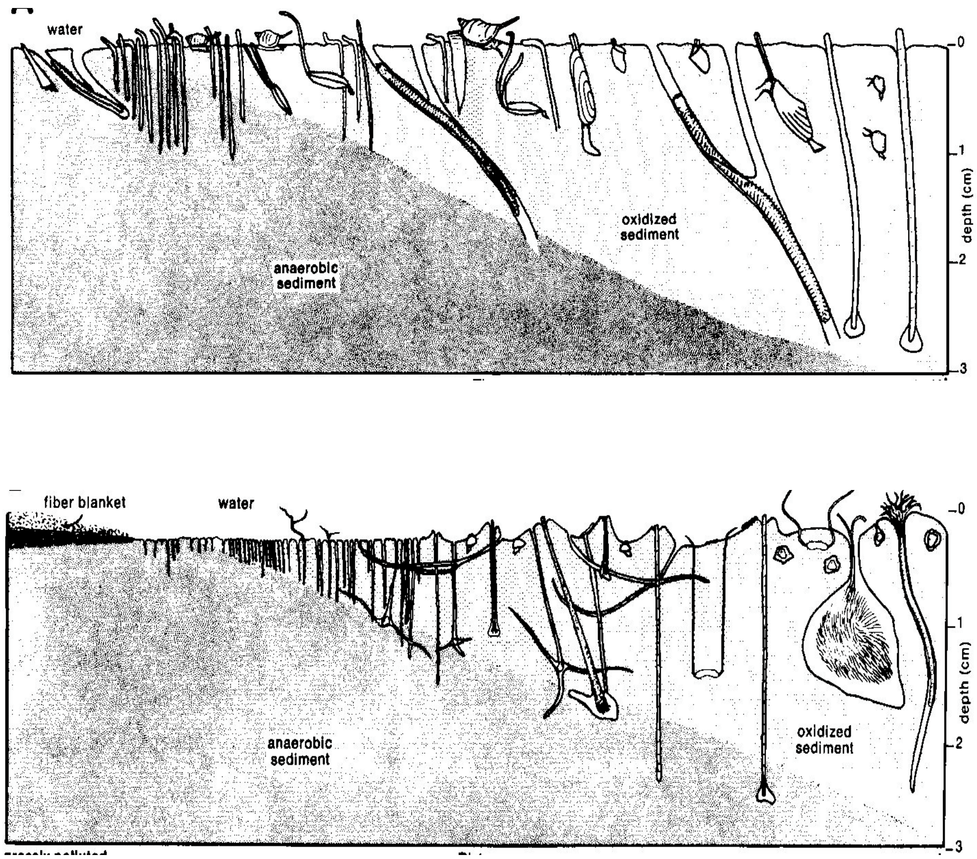

Figure 4: The development of infaunal assemblages over time following a major disturbance. Shown in both diagrams. Pioneering species (left side) tend to be sedentary tubicolous organisms that live near the sediment-water interface and feed near the surface or from the water column. Bioturbation rates are low. High-order successional species (right side) tend to be dominated by bioturbating infauna that feed at depth within the sediment. Particle mixing rates are high. Species diversity is greater with numerous functional groups represented. (Source: Rhoad et al, 1982).

It is assumed that the aggregation of tubes attracts other organisms to further colonize the disturbed area since tube aggregation have been found to have a higher diversity and abundance of non-tube constructing species living in and around them than are found on the adjacent seafloor vacant of tubes (Rhoads, 1982). With the increase in quantity of organic-rich detritus, fecal and pseudofecal material settling between the tubes and the increased supply of dissolved nutrients pumped across the sediment-water interface through the tubes, microorganisms’ colonization and productivity is enhanced (Rhoads, 1982). If the habitat is suitable and food is available, adult organisms from surrounding areas may immigrate to populate the disturbed area (Dernie et al, 2003). As the colonization of the disturbed area increases habitat suitability, settlement of larvae and juveniles either by the mechanisms of habitat selection or through passive mechanism of deposition promotes further colonization (de Wilde, 1991).

The probability of adult organisms from surrounding areas immigrating to populate the disturbed area may be higher than population by recruitment (Dernie et al, 2003). However, Andersen (1971) found that geoduck adults do not migrate from their established positions, and therefore, would only repopulate a harvested area through recruitment efforts. The current TAC harvesting strategy set by DNR and WDFW is predicted to preserve 40% of the unharvested spawning potential of the commercial population (DNR, 2001; Goodwin and Bradbury, 2000). Goodwin and Bradbury’s (2001) study of 15 fished tracts found an average of 72% removal of geoduck density.

Remaining geoduck on a harvested tract may have lower reproduction and growth due to the environmental stress induced by the harvest. Lauritsen (1991) reported that a study of growth and reproduction in clams in Cumberland Sound, Georgia, showed that physiological changes and reduced growth and reproduction can be correlated to environmental stress. The study found that clams (*Mercenaria mercenaria*) in disturbed areas had lower mean reproductive efforts and substantially lower growth rates. Lauritsen believed that the study indicated that the clams were devoting their available energies to their maintenance rather than reproduction.

The recovery of the geoduck resource in fished tracts may be contingent on the geoducks that are unavailable for harvest to sustain the resource. Three-quarters of the total estimated geoduck biomass in Puget Sound is outside the commercial harvest tracts, and therefore, not available for harvest by the commercial fishery. It is not unreasonable to assume that three-quarters of a large population should be able to maintain the population. However, the population is spread throughout the Sound and the commercial tracts are located in areas with high geoduck abundances. As the geoduck populations within the tracts are reduced and all the geoduck populations become fragmented will the geoduck bordering the tracts, possibly in lower abundances, have the ability to return the populations within the tracts to preharvest abundances? Habitat conditions may not be suitable after the harvesting event for geoduck larvae settlement. In addition, the early successional colonization of the disturbed area may result in community dynamics that are not conducive for geoduck larvae settlement and survival.

D. Nutrient Cycling

Artificially resuspended sediments have important implications for nutrient cycling (Pilskaln et al, 1998). Resuspension can result in higher nutrient concentrations in the water column by releasing nutrient rich pore water, desorption or absorption of nutrients from or to particles, and stimulated remineralization with oxidization in the oxygen rich water column (Tengberg et al, 2003). Nutrients are naturally released from the sediment pore water through diffusion; however, a disturbance resuspending as little as 2.4 centimeters of sediment would significantly increase the amount of nutrients available in the water column (Tengberg et al, 2003). Some elements adsorb to suspended particles, whereas, others may detach from particles causing changes in the water column chemistry. Resuspended particles in the water column have a larger surface area exposed and available for microorganisms, such as bacteria, to colonize and continue their remineralization processes utilizing the available oxygen (Tengberg et al, 2003). Studies have shown that resuspension can increase oxygen consumption in the water column by 10 times the normal (Tengberg et al, 2003). This increase in oxygen consumption added to other factors such as oxygen consumption by primary production and the utilization of oxygen for decomposition can lead to anoxic conditions in the water column which could result in fish kills.

The balance of nutrient in the water column is skewed by a pulse of nutrients resulting from a large harvesting disturbance. After the resuspension of sediment by the harvesting, benthic biological activity is reduced as a result of mortalities and relocation of organisms and the reduction in oxygen availability. With benthic biological activity reduced, remineralization is reduced (Tengberg et al, 2003) which results a decrease in nutrient flux across the sediment-water interface. Primary production in the water column is dependent on the nutrients supplied by the benthic process, and therefore, the entire food web can be impacted. Oxygen consumption decreases with the reduction of nutrient and primary production (Tengberg et al, 2003). Without further artifical resuspension by harvesting and anthropogenic nutrient inputs the system would recover its balance.

F. Toxic Effects

1. Release of Eggs & Cycts

Marine sediments are like seed storage banks for many planktonic organisms. Resting eggs and encysted individuals enable the organisms in a dormant resting stage to withstand environmental extremes (Anderson, 1997). Benthic cysts and eggs can remain in a dormant resting stage in the sediment until suitable growth conditions are present or are indicated by their endogenous annual clock (Anderson, 1997; Marcus 1986). Eggs and cysts are moved through natural bioturbation within the sediment and are released into the water column where hatching can occur. Some eggs and cysts may remain within a few centimeters of the surface throughout the winter and be able to germinate the spring or summer (Keafer et al, 1992). Other eggs and cysts are biologically mixed deeper into the sediment. In dynamic sediment environments, cysts and eggs can be rapidly buried to depths of 12 centimeters or greater and may never be released into the water column (Keafer et al, 1992). The natural bioturbation moving cysts and eggs to the surface plays a vital role in the stabilization of the pelagic population and community dynamics in the water column and is an important factor in ensuring long-term population persistence (Anderson, 1997; Raffaelli et al, 2003).

The vertical distributions of cysts and eggs below the water-sediment interface are shaped by physical processes such as mixing, sedimentation, resuspension, and erosion and biological processes of deposition, germination, and mortality (Keafer et al, 1992). Bioturbation is the primarily factor in the vertical distribution of cysts and eggs. A study by Keafer et al (1992) showed that within 1 month of settling on the bottom, eggs and cysts could be buried to a depth of 5 centimeters and after 6 months or more: 11 to 15 centimeters. They found that peak abundances were typically 4 to 8 centimeters below the sediment surface. In a dynamic community, vertical profiles become homogeneous over time (Keafer et al, 1992) indicating a stabilization of the release and burial of cysts and eggs. The peaks are not a result of a pulse input that is moved uniformly deeper but the result of dynamic bioturbation, mortalities and germinations over time.

Eggs and encysted individuals can remain dormant buried in sediments for months to decades depending on the species.

Little is known about the longevity of individual species' buried cysts and eggs (Keafer et al, 1992). Rapid biological mixing makes it difficult to estimate the ages of resident eggs and cysts. However, cysts at depths of 20 or more centimeters are estimated to be approximately 100 years old. Many cysts and eggs buried deeply eventually die (Keafer et al, 1992).

Water jet harvesting turns over the sediment and releases buried cysts and egg into the water column. Once in the water column, the cysts and eggs have access to light and oxygen and are able to germinate if the water conditions are right (Keafer et al, 1992). Dinoflagellate cysts in the Puget Sound may result in toxic algal blooms that may result in commercial shellfish bed closures due to high levels of paralytic shellfish poisoning (PSP) toxicity in the shellfish. PSP is not only harmful to humans but has also been identified as the cause of mass mortalities in birds, seals and sea otters that feed on shellfish (Determan, 2003). The decomposition of the detritus resulting from a large bloom can cause abnormal anoxic conditions that will cause fish kills and upset the normal balance of the Puget Sound, thus a large influx of algal cysts or planktonic eggs into the water system could have detrimental effects on the food web (Puget Sound Action Team, 2003).

In areas that have been stressed by harvesting, organic loading and/or periodic anoxic events, the well-mixed layer is reduced since the recovering benthic communities are dominated by opportunistic organisms that feed and burrow close to the sediment-water interface. Since bioturbation is shallow cysts and eggs are buried effectively and reside close to the sediment surface (Keafer et al, 1992; Marcus, 1986). This increases the likihood of all the cysts and eggs deposited since the event to germinate possibly creating another pulse of organisms into the water column. It can be assumed that large blooms produce large new crops of eggs and cysts, which may create a cycle of growing and spreading blooms.

Dinoflagellate blooms can occur in Puget Sound from early spring to late fall. Toxic dinoflagellates blooms are unpredictable in time and in space due to a lack of knowledge regarding the environmental factors, natural and anthropogenic, which are catalysts for a bloom (Determan, 2003). However, studies have found that blooms are closely linked to cyst benthic seedbeds (Anderson, 1997). PSP levels began increasing in Puget Sound in the 1970's (Determan, 1998) corresponding with the initiation of the commercial geoduck harvest in Washington State. Therefore, the assumption can be made that the release of cysts and eggs into the water column by the commercial geoduck harvest may upset the balance of the Puget Sound ecosystem. Research is needed regarding the correlation between commercial geoduck harvest activity and phytoplanktonic blooms and whether or not the commercial geoduck harvesting activities are significantly impacting the ecosystem balance in Puget Sound by increasing toxic algal blooms.

2. Release of Contaminants, Pollutants and Dissolved Metals

Geoduck water jet harvesting disturbance of the sediments can cause contaminant remobilization of previously buried contaminants. As an important reservoir for contaminants, fine grained bottom sediments have a sorptive nature, and therefore, tend to accumulate contaminants, and thus reduce toxic bioaccumulation potential of commercially important fisheries organisms (Eggleton et al, 2004). Artificial resuspension can change both the redox potential (Eh) and pH of the sediment chemistry which as research has shown can accelerate desorption, partitioning, bacterial degradation and the oxidation of organic contaminants. Exposure to a different chemical environment can result in not only desorption of the contaminants, but also, the transformation of the contaminants into more bioavailable or toxic chemical forms (Eggleton, et al, 2004)

V. Summary of Harvesting Impacts

1. Organisms are exposed to predation, crushed, damaged, buried or suspended and carried away by the currents (Currie et al, 1996; Snelgrove, 1999; L. Watling et al. 1998).

2. Many subtidal communities that are less prone to disturbances have fewer mobile species; therefore, mortality rates are higher. Small patches and natural disturbances of foraging organisms such as fish and crab are small scale in comparison to commercial geoduck harvesting impacts. The larger the disturbance the more impact there is on community resilience.

3. Habitats are destroyed. Commercial geoduck harvesting may homogenize the area by breaking up structures and disturbing

materials more evenly, reducing the structural complexity of the area (Hewitt et al, 2005).

4. Burrows of late successional assemblages are often larger and less numerous than that of opportunistic assemblages. Opportunistic assemblages result in increased flux across the sediment-water interface; less water content in the sediment which inhibits the microbial activities and remineralization; shallower oxidized zone; fewer organisms; and less diversity.

5. Commercial geoduck harvesting causes changes in nutrient fluxes across the sediment-water interface. Resuspension releases nutrients from pore water and desorption from particles; however, other nutrients may decrease in the water column through adsorption to particles changing the availability of nutrients in the water column. Nutrients released from the sediment utilize oxygen to remineralize increasing oxygen consumption dramatically at the time of resuspension. A post-harvest decrease in nutrient flux is predictable with a reduction of biological activity and oxygen availability resulting in decreased remineralization.

6. The disturbed sediment loses stability and grain size distribution is changed with resuspension. The resuspended sediment settles in

an unconsolidated form and may be susceptible to resuspension and erosion by currents and waves.

7. Long term changes in the community structure and dynamic can be expected. The total harvestable geoduck population will be eventually reduced by 40-62% of the original unfished biomass. The population recovery time without harvesting is, on average, 39 years.

8. Benthic and pelagic systems are coupled in that benthic processes and patterns are likely to affect pelagic processes and patterns (Raffaelli et al, 2003). Removal of geoduck and incidental removal of other species may cause functional and/or feeding pattern changes in ecosystem.

9. The release of eggs and cysts may upset the stability of the pelagic population and community dynamics in the water column (Anderson, 1997; Raffaelli et al, 2003). In addition, the release of eggs and cysts may result in toxic algal blooms that can cause commercial shellfish bed closures, mortalities in birds, ocean mammals and fish (Determan, 2003) or abnormal anoxic conditions.

10. Released contaminants, pollutants and dissolved metals into the water column become potentially available for bioaccumulation by commercial important species.

Following is a summary of possible effects of commercial geoduck harvest discussed throughout this paper:

	Possible Effects
Individual	Increased mortality Energetic cost of re-establishing Effects on reproduction Effect on food availability Availability of space to re-colonize Effect of competition for food resources
Population	Changes in density Changes in recruitment intensity and/or variability
Community	Changes in species diversity Changes in species abundances Changes in productivity Changes in patterns of energy flow or nutrient re-cycling
Benthic/Sediment	Changes in food sources Change in water content and oxygen availability Change in nutrient content Changes in sediment composition and cohesiveness Decreased porosity Changes in habitat structure Higher susceptibility to erosion
Pelagic	Changes in nutrient content Changes in rate and type of primary production Increased oxygen consumption Changes in trophic interactions Changes in water clarity/level of turbidity

Table 3: Possible Effects of Commercial Geoduck Harvest at different Levels: Infaunal Biological Organization and Benthic and Pelagic Environments. (Source: Hall, 1994)

VI. Conclusion

It is essential to recognize that the consequences and risks of the commercial geoduck harvesting include many factors in addition to the direct effects on the target species and other commercially important species (Dayton, 1995.) Infauna provide a variety of important ecological functions that are critical in the uptake and recycling of nutrients and energy in aquatic ecosystems The largest abundances of infauna occur in the top 2 centimeters of the oxidized layer; however, organisms are typically distributed to a depth of 15 centimeters (Probert, 1984). Water jet harvesting can disturb sediments to a depth of 100 centimeters (DNR, 2001; Goodwin et al, 1987). Since the water jets disturb to a much greater depth than the infauna inhabit, all the infauna are impacted by the hole excavation. It is unlikely that any organisms escape impact.

Commercial geoduck harvest results in modifications to the surface topography that causes changes to the hydrodynamics and food supply, and therefore, results in community compositional changes. Sediment composition, structure and stability, as well as community composition including species abundances and diversity are altered. Alterations of sediment stability and composition also contribute to community changes. Changing the community composition may cause irreversible changes in the ecosystem functions and important nutrient cycling processes could be lost.

Organisms removed or killed may play important roles in sediment cohesiveness and stability, and therefore, define the community structure. A change in community structure may cause modification to microbial distribution, activity and processes that impact the nutrient cycles (Dayton et al, 1995). The benthic microbial and meioorganisms have not received much attention even though they play a critical role in remineralization necessary for primary production. Important interrelationships between the habitat, the sediment structure and composition, and the organisms need to be realized and evaluated. The most sensitive organisms are the species with low reproductive rates.

The roles and productivity of infauna are being underestimated (Reilly et al, 1999). Considering the role infaunal communities play in nutrient cycles, changes in functional diversity and functional composition of infaunal communities will predictably impact ecosystem processes. Species functions often overlap through their feeding and sediment mixing activities and there are species that can be lost from communities without substantial changes in the communities' functions. The impacts may be positively correlated with the magnitude of differences of functionality among the species. The degree to which species composition and species functional roles represented within the benthic community influence the processes of an ecosystem is not fully understood (Tilman et al, 1997).

Pulses of nutrients, pollutants, and dormant cysted individuals and eggs could be causing the in increases occurrence of phytoplankton blooms, paralytic shellfish poisoning, and other health risks not only to the Puget Sound ecosystem, but also to the people of Washington State. An important concern is the release of unknown organisms or pathogens that have been buried for a 100 plus years. Impacts of cysts and unknown pathogens in the sediment that may be microscopic and difficult to detect may have unexpected repercussions on the ecosystem. It may take some time to discover changes or new organisms in the water column and their impact on other organisms and the ecosystem as a whole. Core samples could be taken to analyze the sediments in tracts designated for commercial geoduck harvesting. A study regarding the origins and spread of toxic algal blooms in Puget Sound, with a comparison to commercial geoduck harvest since 1970, may provide insight regarding the extent that commercial geoduck harvest impacts phytoplankton blooms and the release of pollutants.

Even though harvested areas appear to recover quickly, studies of the effects of removing commercially important species in bulk from other estuarian environments should be reviewed. As discussed in section IV, geoducks dominate the infaunal biomass in many parts of Puget Sound. Are geoducks the dominant infaunal biomass because the geoduck can reach weight of 6.5 kilograms and most infaunal species are very small? Will the removal of approximately 70% of the geoducks and the destruction of the polychaete tube mats impact the recovery of the current community? Have the geoduck interrelationships with other organism and their impact on water clarity been considered?

Geoduck populations within the harvested tracts are reduced and the entire geoduck and infaunal populations will become fragmented. The impacts of the harvest on the community dynamics and substrate composition may change the ability of organisms including the geoduck to recover to their original abundances and diversity. Harvest management strategy that considers community functions is key to managing the impacts and allowing the ecosystem to recover. As with forestry, connectivity is important in maintaining habitat and avoiding fragmentation and isolated patches to allow for regeneration from surrounding areas.

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Appendix 1

Glossary

Anoxia – The absence of oxygen.

Anoxic - Relating to or marked by a severe deficiency of oxygen.

Benthic - Relating to or happening on the bottom under a body of water.

Benthos - 1) The collection of organisms living on or in sea or lake bottoms. 2) The bottom of a sea or lake.

Berm - A mound or bank of earth/sediment.

Biogenic - 1) Produced by living organisms or biological processes. 2) Necessary for the maintenance of life processes; sleep and food and water are among the biogenic needs of the organism.

Bioturbation - The reworking of sediment by organisms that live in and on the sediment. Bioturbation is an important factor influencing the sediment structure and composition and is an essential element of the food web. Bioturbation increases the depth of the sediment aerobic habitat, the area available for microorganism colonization (Probert, 1984). Organisms rework the sediment through feeding, burrowing or tube construction and mobility activities.

Copepods - Any of numerous minute marine and freshwater crustaceans of the subclass Copepoda, having an elongated body and a forked tail.

Cysts - A small capsule-like sac that encloses certain organisms in their dormant or larval stage.

Demersal - Dwelling at or near the bottom of a body of water, ie. a demersal fish.

DNR – Washington Department of Natural Resources.

Egestion – The act or process of discharging undigested or waste material from a cell or organism.

Eutrophication - Waters rich in mineral and organic nutrients promotes a proliferation of plant life, especially algae, which reduces the dissolved oxygen content and often causes the extinction of other organisms.

Fauna – (used with a sing. or pl. verb) 1) Animals, especially the animals of a particular region or period, considered as a group.

Fines – Silt and clay less than 63 microns in size.

Food chain - Describes a single pathway that energy and nutrients may follow in an ecosystem. There is one organism per trophic level. They usually start with a primary producer and end with a top predator. Example of a food chain: phytoplankton → copepod → fish → squid → seal → *Orca*

Heterogeneous - Consisting of dissimilar parts: consisting of parts or aspects that are unrelated or unlike each other.

Homogeneous – 1) Of the same or similar nature or kind; 2) Uniform in structure or composition throughout.

Infauna – Organisms that live in the sediment or at the sediment-water interface.

Intertidal - Of or being the region between the high tide mark and the low tide mark.

Interstitial - Relating to or situated in a space, especially a small or narrow one, between things or parts (sediment particles).

Macrofauna - Organisms larger than 300 µm

Meisofauna - Organisms that are 44 to 300 µm.

Microfauna - Organisms that are smaller than 44 µm.

MLLW (Mean Lower Low Water) – The arithmetic mean of the lower low water heights of a mixed tide observed over a specific 19 year Metonic cycle at a specific tidal reference station. Used to correct ambient depths (from diver depth gauges) to a standard tidal datum.

Mortality Rate – The number of organisms which die divided by the initial number.

Natural Mortality Rate – The ratio of number of organism which die from non-fishing causes per unit of time to the population abundance at that time, if all dead organisms were to be immediately replaced so that the population does not change.

Nematodes - Any of several worms of the phylum Nematoda, having unsegmented, cylindrical bodies, often narrowing at each end, and including parasitic forms such as the hookworm and pinworm. Nematodes are also called roundworm.

Organism - An individual form of life, such as a plant, animal, bacterium, protist, or fungus; a body made up of organs, organelles, or other parts that work together to carry on the various processes of life.

Pelagic - Relating to or living in open ocean or sea water rather than inland waters.

Phytoplankton - Minute, free-floating aquatic plants.

Primary Production - Is the production of organic compounds from inorganic materials principally through the process of photosynthesis (though chemosynthesis also plays a role). The organisms responsible for primary production are known as **primary producers** or autotrophs, and form the base of the food chain. In oceanic ecosystems, algae are generally responsible.

Recruitment – The entry of a new organism into the population.

Recovery time – The estimated time for a population to return to the predisturbance density and biomass level.

Seston - Suspended seston, which is composed of organic and inorganic particles.

Secondary Production - The production of living material by herbivores. Usually expressed as grams carbon per meter square per year.

Solute - A substance dissolved in another substance.

Substrate - A surface on which an organism grows or is attached.

Subtidal – At a depth that is never uncovered by the tides.

TAC (Total Allowable Catch) – The number or weight of fish which may be harvested in a specific unit of time. As used in this report, the product of the estimated biomass of harvestable geoducks and the recommended annual harvest rate.

Tract – A subtidal area with defined boundaries which contains geoducks.

Trophic - Of or involving the feeding habits or food relationship of different organisms in a food chain.

µm – micron – A unit of length equal to one millionth (10-^{6}) of a meter.

Water column – Of or relating the layers of water from water surface to bottom.

WDFW – Washington Department of Fish and Wildlife.

Appendix 2

Conversion Table

Measurement	Multiply By	To Obtain
Millimeters (mm)	0.03937	Inches (in)
Centimeters (cm)	0.3937	Inches
Meters (m)	3.281	Feet (ft)
Square Meter (m^2)	10.76	Square Feet (ft^2)
Grams (g)	0.3527	Ounces (oz)
Kilograms (kg)	2.205	Pounds (lbs)
Hectare	2.471	Acre

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