Technical Report 2006-04

Native Shellfish in Nearshore Ecosystems of Puget Sound

Prepared in support of the Puget Sound Nearshore Partnership

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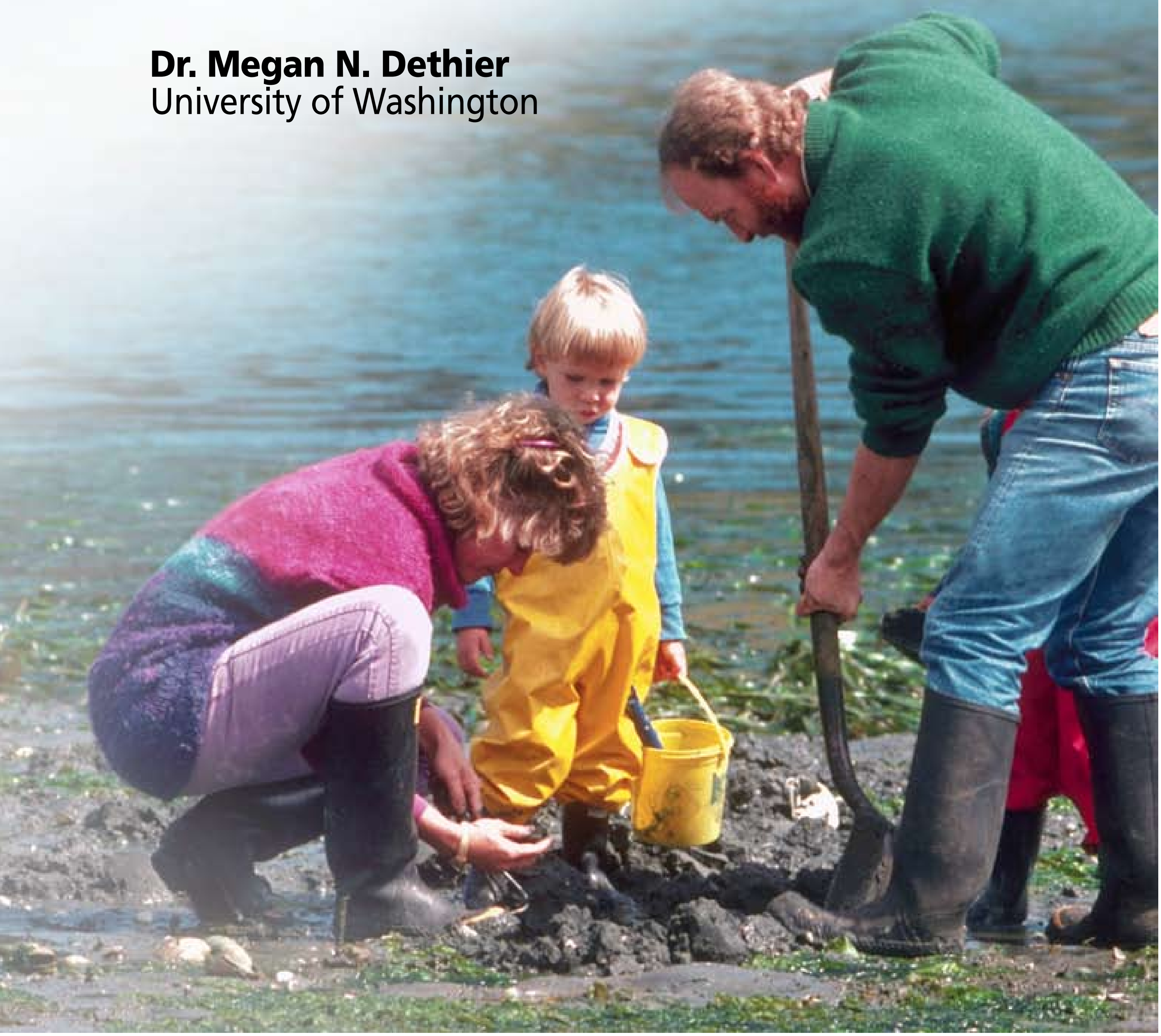

Valued Ecosystem Components Report Series

Puget Sound Nearshore Partnership

Restoring Our Ecosystem Health

The Puget Sound Nearshore Partnership (PSNP) has developed a list of valued ecosystem components (VECs). The list of VECs is meant to represent a cross-section of organisms and physical structures that occupy and interact with the physical processes found in the nearshore. The VECs will help PSNP frame the symptoms of declining Puget Sound nearshore ecosystem integrity, explain how ecosystem processes are linked to ecosystem outputs, and describe the potential benefits of proposed actions in terms that make sense to the broader community. A series of "white papers" was developed that describes each of the VECs. Following is the list of published papers in the series. All papers are available at *www.pugetsoundnearshore.org.*

Brennan, J.S. 2007. Marine Riparian Vegetation Communities of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-02. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Buchanan, J.B. 2006. Nearshore Birds in Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-05. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Dethier, M.N. 2006. Native Shellfish in Nearshore Ecosystems of Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-04. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Eissinger, A.M. 2007. Great Blue Herons in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-06. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Fresh, K.L. 2006. Juvenile Pacific Salmon in Puget Sound. Puget Sound Nearshore Partnership Report No. 2006-06. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Johannessen, J. and A. MacLennan. 2007. Beaches and Bluffs of Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-04. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Kriete, B. 2007. Orcas in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-01. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Leschine, T.M. and A.W. Petersen. 2007. Valuing Puget Sound's Valued Ecosystem Components. Puget Sound Nearshore Partnership Report No. 2007-07. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Mumford, T.F. 2007. Kelp and Eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-05. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Penttila, D. 2007. Marine Forage Fishes in Puget Sound. Puget Sound Nearshore Partnership Report No. 2007-03. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Front cover: Recreational clam harvesting on Puget Sound.

Back cover: Geoduck, left, and Manilla clams. (Photos courtesy of Washington Sea Grant.)

Contents

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The Puget Sound Nearshore Partnership Steering Committee initiated the concept of this paper and the others in this series. The Nearshore Partnership Project Management Team (PMT) — Tim Smith, Bernie Hargrave, Curtis Tanner and Fred Goetz — oversaw production of the papers. The Nearshore Science Team (NST) played a number of roles: they helped develop conceptual models for each valued ecosystem component (VEC), in collaboration with the authors; individual members were reviewers for selected papers; and members were also authors, including Megan Dethier, Tom Mumford, Tom Leschine and Kurt Fresh. Other NST members involved were Si Simenstad, Hugh Shipman, Doug Myers, Miles Logsdon, Randy Shuman, Curtis Tanner and Fred Goetz.

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Executive Summary

Native shellfish in Washington state are of high ecological, economic, cultural, and recreational value. Ecologically, many of them filter nearshore waters, contributing to water quality. They also serve as predictable sources of food for carnivores in nearshore habitats. Others are predators that are part of the ecological balance of nearshore ecosystems. Most have larvae or juveniles that spend time in the water column, where they provide food for a variety of valued fishes. Culturally, they have been a critical part of the subsistence and culture of native peoples for centuries. Economically, nearshore shellfish in Puget Sound have a commercial value of almost $100 million a year; roughly $60 million of this is from sales of the non-native Pacific oyster, but more than $40 million is from native crabs, clams, and mussels. Recreationally, personal harvest of shellfish is a very popular activity despite problems with water quality in many regions.

Native shellfish in Puget Sound are diverse, both in terms of species and in the ways that they use nearshore ecosystems. Species include crabs, numerous clams, the Olympia oyster, mussels, shrimp, abalone, and various others. In Puget Sound, all major shellfish species, with the exception of shrimp, use nearshore ecosystems for part or all of their life histories. This white paper focuses on geoduck clams, Dungeness crabs, hardshell clams, and Olympia oysters.

Geoduck clams are especially abundant in the south sound, buried deeply in mud or sand in the low intertidal and subtidal zones. Dungeness crab are present throughout the state's waters but in Puget Sound are most abundant in the northern portions. Adults are found primarily in the subtidal zone in soft sediments, but the juveniles rely heavily on intertidal habitats with structural complexity, such as eelgrass beds. Their larvae spend long periods (months) in the water column before returning to the nearshore zone to settle.

Hardshell clams, including littleneck, butter, and horse clams, are abundant throughout Puget Sound, primarily in the intertidal and shallow subtidal zones. All prefer sediment mixed with gravel or cobble, and their populations are sometimes enhanced by adding gravel to sandy or muddy beaches.

Native Olympia oysters grow best in shallow subtidal muddy habitats but prefer to settle as larvae onto pieces of harder substrate such as shells or pebbles. Populations of native oysters have virtually disappeared due to overharvesting and pollution, but there are increasing efforts to reestablish them.

Few data exist on the status of natural populations of these shellfish, or on their trends through time. The Washington Department of Fish and Wildlife (WDFW) has been tracking both recreational and commercial exploitation of many species since the 1970s. Landings of most species have stayed roughly the same or have increased during this time period. In most cases, however, data on catch per unit effort (as for commercial fisheries) are lacking, so harvest increases may simply be the result of greater effort. Recreational harvest rates of clams per trip (a catch-per-effort statistic) have been fairly stable since 1990, although the harvest of several native clams appears to have declined relative to introduced Manila clams, which are easier to dig. The only shellfish that has clearly undergone a major decline in natural populations is the Olympia oyster, which is no longer commercially viable. There are also concerns about long-term declines in geoduck populations. Even for apparently stable populations, however, there are clearly problems in Puget Sound; water quality issues often affect peoples' ability to use shellfish.

Threats to shellfish in Puget Sound come from a variety of directions. As illustrated by Olympia oysters, commercial and recreational overharvesting can be an issue. The trend toward aquaculture reduces the pressure on native populations, but most cultured species are non-native. However, virtually all shellfish are affected by human alterations of key ecosystem processes, such as sediment supply. All the shellfish described in this report have distinct types of sediment in which they recruit and/or grow the best; thus, any process that alters sediment amount, grain sizes, organic content, etc., may negatively impact local shellfish populations. These alterations can come from changes in runoff from land, in sediment loads carried by rivers and streams, and in sediment supply from bluffs that have been hardened. Many of these processes could be restored, with likely positive impacts on shellfish. Shellfish in both adult and larval stages are also strongly affected by water column characteristics. Key parameters include temperature and salinity, turbidity, oxygen, pollutants, and food types and concentrations. All these can be affected by land use, shoreline modifications, stormwater and sewage discharge, industrial discharge, and other human activities, many of which could be restored either locally or throughout the sound. Factors that humans can alter, to the detriment of shellfish, include habitat characteristics like the abundance of eelgrass and the type and abundance of predators, competitors and parasites (e.g., aiding the establishment of invasive species).

Preface

Native shellfish in Puget Sound have considerable value ecologically, socially, and culturally. The ecological functions of shellfish vary greatly with their place in the food chain. Clams and oysters are filter feeders, which help to maintain water clarity and quality by clearing it of excess plankton (demonstrated in Chesapeake Bay and elsewhere). In addition, they are the main source of food for higher level carnivores such as crabs, moonsnails, and seastars. Dungeness and other crabs are important in nearshore food chains as both predators and prey. They are upper level carnivores, consuming a wide variety of prey including mollusks, crustaceans, and fishes. Younger stages serve as important prey items for a number of predators. As larvae, crabs are consumed by Pacific herring, Pacific sardines, rockfishes, and coho and Chinook salmon. As benthic juveniles, they are eaten by starry flounder, English and rock sole, lingcod, rockfish, sturgeon, sharks, skates, harbor seals, and sea lions. Even adult crabs are eaten by some of the larger vertebrate predators.

Native shellfish also have immense value to humans, both economically and culturally. Shellfish in Puget Sound are important symbols of the region's heritage; they were and are of immense importance to the subsistence and culture of native peoples from numerous coastal tribes. They are also very important both recreationally and commercially for non-native peoples. At this time, the major nearshore recreational shellfish resources in Puget Sound are crabs (both Dungeness and red rock crabs), oysters (primarily introduced Pacific oysters, but with increasing interest in bringing back Olympia oysters), clams (including littleneck, butter, horse, and introduced Manila and softshell clams), and a variety of species of less common interest, including snails, sea cucumbers, sea urchins, and others. Annually, recreational shellfish harvesters collect nearly two million pounds of clams and oysters from around the sound (*www.psat.wa.gov/About_Sound/Economic.htm*). Discussions with shorefront property owners in Puget Sound suggest that for many, a significant contributor to the value of their parcels is the shellfish that can be harvested there. Significant commercial harvests of shellfish in Puget Sound include fisheries for geoducks, Dungeness crab, oysters (primarily introduced species), and hardshell clams. The current annual value of commercial native shellfish is approximately $40 million, and oysters add another $58 million. Thus nearshore ecosystem processes that contribute to the health of shellfish populations are important both to the rest of the ecosystem and to society.

Nearshore Habitat Requirements

Because the native shellfish found in Puget Sound are so diverse, discussion of their habitat requirements, status and trends will focus on four representative species: Dungeness crab, native littleneck clams, geoduck clams and native oysters. These are illustrative of most of the functional groups that include shellfish in Puget Sound (summarized in Table 1).

After their early life history as planktonic larvae, Dungeness crab (*Cancer magister*) are epibiota (living on the surface) and predatory. Similarly, the bivalves all have planktonic larvae, but as adults oysters are epibiota and filter feeders, littleneck clams (*Protothaca staminea*) are infaunal (living in the sediment) filter feeders living in the intertidal zone, and geoducks (*Panope generosa*) are infaunal filter feeders living in deeper water. A few other shellfish, not discussed in detail, are deposit feeders, such as *Macoma* spp. clams and sea cucumbers (*Parastichopus californicus*). The four species covered in detail are also some of the most important species in terms of human harvest, both commercially and recreationally. In many cases their habitat requirements are similar to those of other species; e.g. littleneck clams are similar to other hardshell clams, such as Manila and butter clams. Other shellfish of ecological or commercial value in Washington are not discussed in detail. Some of these are nearshore dependent (e.g., sea urchins and sea cucumbers), whereas others are primarily found in deeper waters outside of nearshore ecosystems (e.g., scallops, most shrimp, and squid).

Non-native shellfish species are not discussed in detail, although basic information is given below for several key species. It is critical to note, however, that the "ecosystem services" that benefit native shellfish, such as natural sediment processes and water free of pollutants, also benefit non-native shellfish that humans value. In addition, ecosystem services *provided by* native shellfish are probably also provided by non-natives.

Table 1. Shellfish species discussed in this paper.

Native species

Common name	Scientific name	General habitat type	Trophic type
Dungeness crab	*Cancer magister*	inter- and subtidal sediments	predator, scavenger
red rock crab	*Cancer productus*	very broad	predator, scavenger
geoduck	*Panopea generosa*	buried in intertidal and subtidal sediments	filter feeder
littleneck clam	*Protothaca staminea*	buried, intertidal sediments	filter feeder
butter clam	*Saxidomus giganteus*	buried, intertidal sediments	filter feeder
horse clam	*Tresus capax and nuttallii*	buried, intertidal and subtidal sediments	filter feeder
cockle	*Clinocardium nuttallii*	near surface, intertidal sediments	filter feeder
bentnose clam	*Macoma spp.*	buried, intertidal sediments	deposit feeder
mussel	*Mytilus spp.*	surface, rocks or pilings	filter feeder
sea cucumber	*Parastichopus californicus*	surface, subtidal rock or sediment	detritus feeder
pinto abalone	*Haliotis kamtschatkana*	surface, wave exposed rock	herbivore
sea urchin	*Strongylocentrotus spp.*	surface, subtidal rock	herbivore
Olympia oyster	*Ostreola conchaphila*	surface, subtidal mud, rock and shell	filter feeder

Non-native species

Pacific oyster	*Crassostrea gigas*	surface, intertidal mud or shells	filter feeder
softshell clam	*Mya arenaria*	buried, intertidal sediments	filter feeder
Manila clam	*Venerupis philippinarum*	buried, intertidal sediments	filter feeder
Purple clam	*Nuttallia obscurata*	Buried, intertidal sediments	deposit feeder

Dungeness crab: *Cancer magister*

Dungeness crab are found in all Washington waters, both on the outer coast (especially in the coastal estuaries, during portions of their life history) and in all the inside waters (Figure 1). There have also been some harvests in the Nisqually area. (P. Dinnel pers. comm).

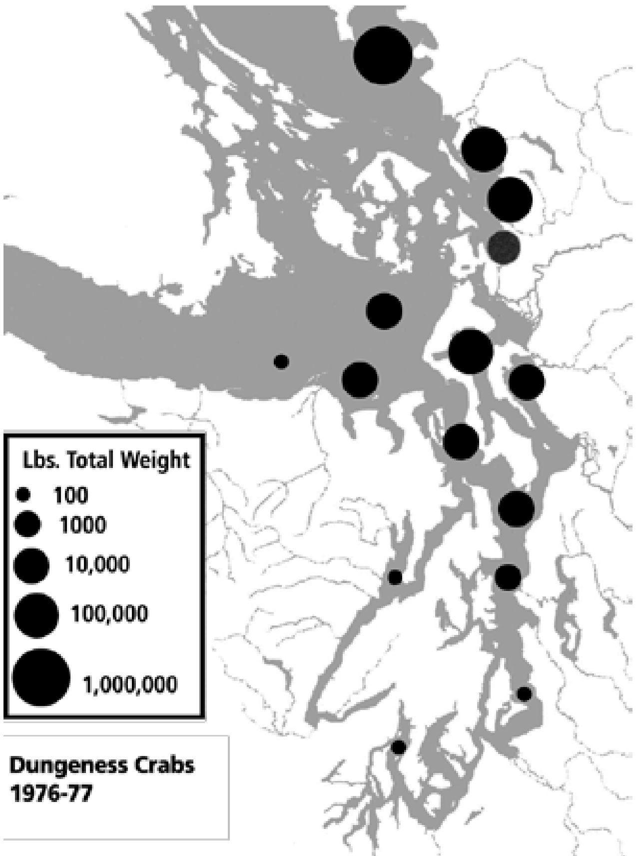

Figure 1. Harvest locations of Dungeness crabs; from Cheney and Mumford (1986)

Like many marine invertebrates, Dungeness crabs use different habitats during different parts of their life cycle. Judging by where most adult crabs are caught by commercial fisheries, their largest populations are found subtidally, on sandy or muddy bottoms, in waters deeper than 100 meters (Dinnel et al. 1988). However, they are also found abundantly in the nearshore subtidal and even in intertidal zones, on substrates ranging from mud to clean sand or gravel. They are often found associated with nearshore eelgrass beds.

Dungeness crabs are predators and scavengers, feeding on a wide range of prey. Juveniles prefer small mollusks and crustaceans, whereas adults eat mostly clams, but also crustaceans and fishes (Butler 1954, Gotshall 1977). Crabs are in turn consumed by a variety of other organisms, depending on the stage in their life history. Larvae (in the plankton) are eaten by coho and chinook salmon and rockfishes (Orcutt et al. 1976, Prince and Gotshall 1976, Reilly 1983). Benthic juveniles are eaten by a wide variety of fishes (Reilly 1983). Adults get large and have effective anti-predator defenses, but are still consumed to some degree by fishes, seals, octopuses, and each other, especially following molting when their shells are very soft.

Adults move out of estuaries or other nearshore areas to mate, generally from March to April (summarized in Pauley et al. 1986). Females store sperm and use them to fertilize eggs extruded in the fall. From October to December, crabs must be buried in sand for the eggs to adhere properly. Fertilized eggs are incubated for two to three months. During egg incubation, females aggregate in high densities in selected areas, to which they show high fidelity (Armstrong et al. 1987, Dinnel et al. 1988). Eggs hatch into pre-zoea larvae from January to April. These larvae move offshore and undergo five molts over three to five months. They may disperse long distances during this period. Eventually they move nearshore again as megalops larvae, which settle to the bottom, often into the intertidal zone. Puget Sound sites receive larvae from both coastal and inland waters. Settlement of larvae of coastal origin peaks in May-June, whereas larvae from Puget Sound populations settle later and over a protracted season, peaking in August (Orensanz and Gallucci 1988, Dinnel et al. 1993). Juveniles in coastal estuaries are most frequently found intertidally in areas of soft substrate containing eelgrass and bivalve shells (Armstrong and Gunderson 1985), whereas Puget Sound juveniles are found most abundantly in areas of gravel with algae, and secondarily in eelgrass. Bare sand habitats are seldom used by juveniles (McMillan 1991, McMillan et al. 1995), probably because the lack of structure provides them with no refuge from predation and desiccation, and there is less potential food. Juveniles in estuaries grow faster than those in coastal waters, suggesting that estuaries are important nursery habitats for yearling and sub-yearling crabs (Stevens and Armstrong 1984). In Puget Sound, Dungeness crab move down out of vegetated intertidal areas into unvegetated subtidal channels after about 10 months (Dinnel et al. 1986), probably because by then they are large enough to be more resistant to predation. Older crabs may move progressively farther subtidally (Dinnel et al. 1986, 1987).

Settlement and survival of Dungeness crabs vary highly from year to year, although recruitment of Puget Sound populations varies less than that of coastal populations (McMillan 1991, McMillan et al. 1995). This reduced variability may be due to the reduced vagaries of larval transport in inland waters as compared to the outer coast, although it is unknown to what extent Puget Sound-origin larvae are retained within the sound versus dispersed offshore and then transported back onshore. The successes of particular year classes are probably determined by larval survival to metamorphosis, which depends on predation, water temperatures, food availability, and currents that carry the larvae toward or away from the nearshore (Armstrong 1983).

Effects of urban pollution on Dungeness adults are not well known, but they are intolerant of low dissolved oxygen. Larvae are highly sensitive to insecticides and heavy metals, as well as to variation in temperature and salinity (Reed 1969); larvae will not metamorphose to megalopae above 20° C. All life stages show highest survival in euhaline (i.e., higher salinity) waters. The reliance of juveniles on estuaries, including eelgrass beds, suggests that this stage may be the most vulnerable to human impacts. Dredging in estuaries, for example, causes severe habitat alteration or loss for Dungeness (Stevens and Armstrong 1984).

Red rock crabs, *Cancer productus*, are not exploited commercially because they are not as large as Dungeness and their shells are heavier in proportion to their body. As adults, they are much more abundant intertidally than Dungeness, although juveniles of both species are common in the intertidal. Red rock crabs occur in sandy, muddy, and gravelly bays, especially where there is eelgrass, and even in rocky situations. Because of this greater accessibility, they are often fished recreationally. Their life history has not been studied in detail.

Native littleneck clams, *Protothaca staminea*, and other hardshell clams

Native littleneck clams are found throughout Puget Sound and in Grays Harbor and Willapa Bay, but are relatively uncommon along the Strait of Juan de Fuca. Unlike many other shellfish species, their populations are not concentrated in one particular portion of the sound (Figure 2).

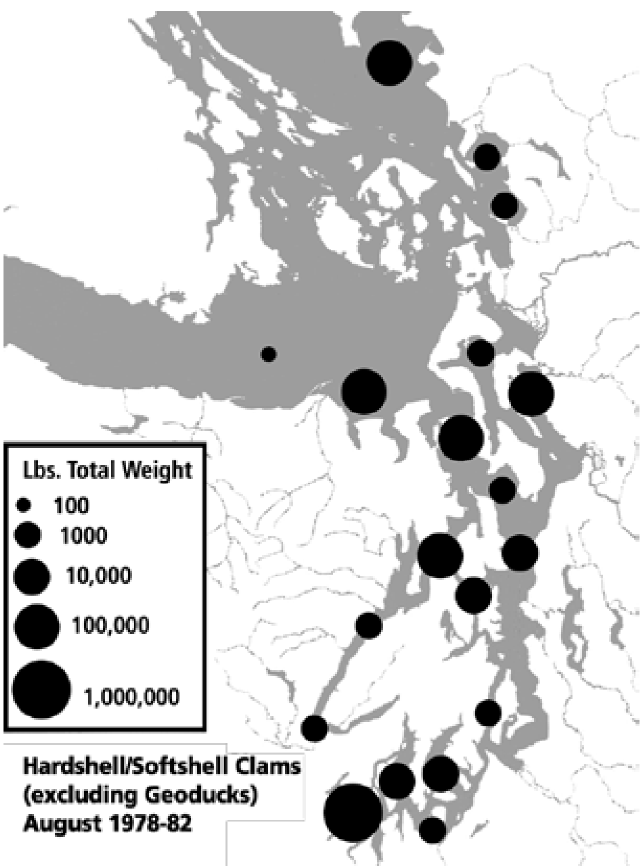

Figure 2. Harvest locations of hardshell clams; from Cheney and Mumford (1986)

These abundant and popularly exploited clams are found primarily in the intertidal zone and shallow nearshore subtidal zone (to about 35m depth), where they live in a variety of substrate types (summarized in Chew and Ma 1987). They are especially common in protected bays and estuaries where the substratum is cobble or gravel mixed with sand or mud and broken shell. They do poorly in fine sand (Fraser and Smith 1928). They are most common in the low and mid-intertidal zone, but growth is fastest at roughly mean lower low water (MLLW) (Houghton 1973). They tend to live near the surface of the sediment (upper 15-20 cm), making them easy prey for recreational harvesters and for natural predators such as moonsnails, seastars, crabs, and even diving seabirds. In addition, demersal fish may nip their siphon tips (reviewed by Chew and Ma 1987).

Littleneck clams are filter feeders that consume plankton, especially diatoms and detritus, apparently with little selectivity (Chew and Ma 1987). They may gain significant nutrition from particulate organic matter produced in the nearshore, such as from eelgrass and benthic algae (C. Simenstad, Univ. of Washington, pers. comm.). Areas near strong tidal currents may enhance growth, whereas quiet water at the heads of bays leads to poorest growth (Smith 1928, Goodwin 1973). However, growth of young clams is impaired in exposed sites where waves move the surface sediment (Fraser and Smith 1928). Adding gravel to beaches that have become too sandy has been shown to provide small clams with protection from wave action and predators (Glude 1978, Schink et al. 1983).

Adult littlenecks can tolerate salinities as low as 20 parts per thousand (ppt), but the optimum for growth is 24-31ppt. They are also tolerant of a wide range of temperatures, but the optimum is 12-18°. Mature adults release planktonic gametes from April to July (Quayle and Bourne 1972), so that fertilization is in the water column. The larval period lasts three weeks or longer in cold water, leading to considerable dispersal potential. Veliger larvae search the bottom before metamorphosis; they may settle in deeper water and move shallower as they grow (Shaw 1985). Reproductive success or failure often seems determined by survival of the larval stage, which is affected not just by temperature and salinity but also by factors such as high turbidity, which reduces larval survival. Postlarval recruitment success is highly variable, apparently more so than for some other clam species (Peterson 1975). Freshwater pulses or freezing may affect intertidal populations of juveniles, and food supply and predation are also important (Chew and Ma 1987). High siltation caused by upland development or nearby dredging can affect subtidal populations by smothering. Burial by decomposing bark from nearby wood processing facilities reduces survival. They are also known to be very sensitive to high concentrations of copper from boat bottom paint (Phelps et al. 1983).

A second species of hardshell clam of great value in Washington state is the introduced Manila clam, *Venerupis* *philippinarum (= Tapes japonica)*. This species was originally imported with seed oysters in the 1930s from Japan. It inhabits the same areas and very similar sediments as native littlenecks. Manilas tend to be found slightly higher on the shore and live closer to the surface of the sediment, making them highly popular with harvesters and predators and reducing their direct competition with native species (Byers 2005). Additions of pea gravel and small rock to beaches can enhance settlement, perhaps because larvae attach a byssal thread to pebbles or shells for settlement. Coarser surface sediments probably also deter predators. Optimum conditions for growth are warmer than those for native littlenecks, 13-21°, and they can tolerate even wider ranges. They require temperatures over 14° for spawning and larval development; peak spawning is in June-July. The larval period lasts three to four weeks but varies with food and temperature. They are highly tolerant of pollution, but like many clams they can concentrate contaminants and paralytic shellfish poisoning (PSP) toxins and thus become inedible for humans.

Butter clams, *Saxidomus giganteus,* have similar distributions to these other two hardshell species, although they tend to be found lower in the intertidal zone (near mean low water) and subtidally. They are most common in sandy and gravelly muds. They are harder to harvest (and less accessible to natural predators), as their larger size enables them to bury as deep as 30 cm. Less is known about their ecological requirements, except that salinities as low as 5-15 ppt slow their growth. Unlike littlenecks, they generally cannot or do not move around once the larvae have metamorphosed, which may mean they have less flexibility to move out of suboptimal conditions. Like littlenecks, butter clams can concentrate PSP toxins, and they retain these for a longer period of time (reviewed in Armstrong et al. 1993).

Geoduck clams: *Panopea generosa (= P. abrupta)*

These very large clams are abundant in Puget Sound (Figure 3) and the Strait of Juan de Fuca but are not found on the outer coast of Washington. They are primarily a subtidal clam, although some areas (e.g., in Hood Canal, Armstrong et al. 1993; C. Simenstad pers. comm.) have populations that extend into the low intertidal zone. Subtidal populations tend to be aggregated in dense beds that are present down to at least 110 meters, but they are most abundant at 9-18 meters, especially in south Puget Sound (Goodwin and Pease 1989).

Geoducks live in substrates ranging from soft mud to small gravel, but are mostly found in stable mud or sand bottoms, often with the sea pen *Ptilosarcus*. Growth is fastest in sand, or mud mixed with sand, but not in gravel or pure mud (Goodwin and Pease 1987). Growth is also best in shallower depths and at higher current speeds. They are filter feeders, like most clams. Predators of these clams include fish (sole and flounders), starfish, crabs, and snails that can consume juveniles. Adults can bury deeply enough to escape from most predators, other than humans.

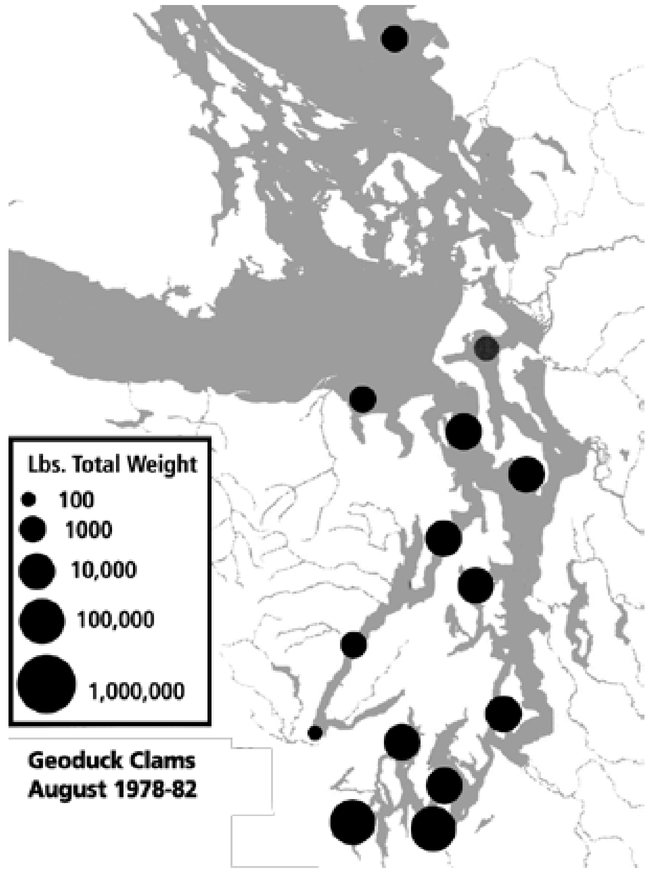

Figure 3. Harvest locations of geoducks; from Cheney and Mumford (1986)

Adult geoducks are tolerant of salinities ranging from 5-35 ppt, but the optimum is above 25 ppt. They can also live in a range of temperatures, but need cold water (<16°) during spawning. Spawning occurs mostly in May and June, with the larval period lasting four to six weeks before settlement. Eggs and larvae need more saline waters than adults (Goodwin 1973). Settlement peaks in mid-July; polychaete tubes are preferred attachment areas. Juveniles stay at the surface attached to other substrates or with a 'sand anchor' until they are 1.5-2 mm long, when they begin to burrow.

As in most bivalves, mortalities during larval and early post-settlement phases are high, so that successful recruitment is low (Goodwin and Shaul 1984). Replenishment of populations post-harvesting thus often relies on 'seeding' of juveniles into appropriate habitats. Recruitment seems highest in areas with adults, contributing to their tendency to be aggregated, but meaning that harvesting adults makes it doubly hard for populations to recover (Goodwin 1978). Juveniles have some ability to move, but adults show little movement. Because of this, deteriorating physical conditions such as anoxic water or excess sedimentation can cause adult mortalities. Marine construction projects have destroyed much geoduck habitat, and aquaculture projects compete with geoducks for space (Goodwin and Pease 1989).

Native Olympia oysters: *Ostreola conchaphila (= Ostrea lurida)*

Olympia oysters were once found in tidal channels, estuarine flats, bays and sounds from Southeast Alaska to Baja California. In Washington, they were especially abundant in the coastal estuaries and in southern Puget Sound and were a subsistence fishery for native Americans (Steele 1957). They are primarily a subtidal species (Hertlein 1959), although they are sometimes found and can be cultured in the intertidal zone. Natural oyster reefs are 0 to 10 meters deep, bordered above by mudflats and sometimes below by eelgrass beds. They primarily occupy soft substrates, but are sometimes found in the intertidal zone attached to undersides of cobbles (Couch and Hassler 1989; reviewed by Baker 1995).

Adults can tolerate a range of temperatures but not extreme heat or cold (Matthiessen 1970), and they do best in salinities over 25 ppt. They spawn in the summer over a prolonged period after the water temperature exceeds 12°C; each individual initially spawns as a male, then alternates functional gender between each spawning cycle (Coe 1932). Fertilization is internal, and larvae are brooded for two weeks before being released into the water column (Baker 1995). The planktonic larval stage is shorter than for clams, lasting only 11-16 days. Larvae metamorphose especially readily on the undersides of old shells, rocks, or wood (Fasten 1931).

Oysters are filter feeders, consuming plankton and particulate organic matter. *Cancer productus* and other crabs are important predators, as well as scaups and scoters (Galtsoff 1930). Oysters can be killed by wastes from pulp mills, and their habitats are adversely affected by silt from highway construction and upland development (reviewed in Armstrong et al. 1993).

The more commonly encountered oysters in local waters at this time are introduced Pacific or Japanese oysters, *Crassostrea gigas,* which form the basis of an expansive aquaculture industry and have naturalized as well. They live in the low-mid intertidal zone down to about seven meters, on firm to mud bottoms. They usually attach to rocks, debris or other oyster shells. They are amenable to aquaculture because they grow larger than most oysters, their 'seed' can be produced in hatcheries, and they are physiologically hardy, especially of high temperatures. They also tolerate a broad range of salinities (10-35 ppt). They are a warmer-water species than the native oyster, and in nature they usually require water over 18° to spawn. Pacific oysters primarily spawn in July and August during high tides, but this only occurs sporadically outside of hatcheries, in bays where water warms up substantially in the summer (e.g., Hood Canal and various inlets in British Columbia). The larval stage lasts two to four weeks depending on temperature; larval growth requires water warmer than 17°, and larval settlement is best in water over 25°. Like other filter feeders (including native oysters) they concentrate contaminants (bacteria or pollutants) from the water column. Bacteria are not harmful to the shellfish, but shellfish use of bacterial food sources makes them risky for human consumption and unavailable for commercial harvest.

Other Nearshore Shellfish

Other nearshore shellfish in Puget Sound include:

Infaunal Filter Feeders:

1. Horseclams, *Tresus capax* and *T. nuttallii*. These large clams generally live in sandy or gravelly mud but sometimes even in stiff clay. They are found from the mid-intertidal zone to about 30 meters depth, and are most abundant at one to five meters below MLLW. Adults dig deep in the sediment, 30-50 cm below the surface.
2. Cockles, *Clinocardium nuttallii,* prefer portions of quiet bays with muddy fine sand but are sometimes plentiful in rather clean sand. Beds of eelgrass growing on mud often support large populations. They have unusually heavy shells and short siphons and are found at or near the surface of the sediment.
3. Softshell clams, *Mya arenaria,* inhabit mixtures of mud and sand or gravel, often in areas of lower salinity and higher on the shore than most clams. They are probably introduced from the Atlantic, where they are a key economic resource.

Infaunal Detritivores:

Clams in the genus *Macoma* (e.g., the bent-nose clam, *M. nasuta*) feed differently from the previously described clams in that they use their siphons to 'vacuum' detritus off the surface of the sediment. Because of this, they tend to have a muddy flavor and are rarely used for human consumption, although they may be harvested as bait or for other uses. *Macoma nasuta* live in the intertidal zone of protected bays, in fine muds or muddy sand; *M. inquinata* inhabit sand, mud or the mixed gravel-sand sediment where hardshell clams are found; *M. secta* prefer cleaner sands (Kozloff 1983). All can be found in eelgrass beds. A related species, the purple varnish clam, *Nuttallia obscurata*, was introduced from Asia and is rapidly spreading through the Pacific Northwest (Mills 2004). It tends to inhabit the mid and high intertidal zone in muddy to mixed-coarse substrates. Unlike *Macoma* species, *Nuttallia* is considered edible.

Epifaunal Filter Feeders:

Edible or bay mussels, *Mytilus trossulus (=edulis*) and *M. galloprovincialis*, are found naturally on rocky shores and also commonly as 'fouling organisms' on pilings and other man-made structures in any protected to exposed habitat. They are also artificially cultured in some areas of Puget Sound. They can live in the intertidal or shallow subtidal to about five meters or sometimes deeper. *M. galloprovincialis* is the most commonly cultured mussel in Washington (usually on off-bottom racks or nets), as it is more disease-resistant than the native mussel (Wonham 2001). All mussels readily take up and concentrate contaminants, and are thus used as 'sentinels' of environmental quality (NAS 1980).

Epifaunal detritivores:

Sea cucumbers, *Parastichopus californicus*, inhabit subtidal rocky or cobble areas where they consume sediment and organic material that settles on the bottom. They thus tend to be more abundant in areas without high currents. Little is known about the life history or ecological importance of these organisms, for instance where the young recruit, but there is a commercial fishery for them.

Epifaunal Herbivores:

1. Pinto abalone, *Haliotis kamtschatkana*, live in shallow subtidal rocky areas with moderate to high wave energies. The only part of the inside waters of Washington where they are found is the San Juan Islands and the Strait of Juan de Fuca. They consume a variety of algal species. There has never been a commercial fishery for this species in Washington. Nonetheless, they have been harvested almost to extinction, primarily by recreational divers and by commercial divers harvesting sea urchins or cucumbers. They are now federally listed as a 'Species of Concern'. The recreational fishery was closed in 1994, but there is concern that current populations are too sparse to reproduce effectively. In addition, their larval period is too short (4-11 days) to allow them to recolonize readily from the rare remaining aggregations (Sea Grant 2004).
2. Sea urchins, *Strongylocentrotus* spp., are herbivores that live in shallow to deep waters on rocky substrates, especially in the northern inside waters and the more exposed waters of the state. They are critical agents of subtidal community structure in rocky areas through their intensive grazing of young and adult seaweeds. They are consumed by seastars, and on the outer coast by sea otters. There are commercial fisheries for several of the species in the San Juan Islands, Strait of Juan de Fuca, and outer coast.

Shellfish Status and Trends

For most of the nearshore shellfish of Puget Sound, there are several decades of good data on harvest rates (commercial and to a lesser extent recreational), presented below. However, it is very difficult to quantify the actual status in the sound of shellfish populations, rather than harvestable areas or harvest rates. Population estimates, when available, only extend over a few years or decades, so it is seldom possible to hindcast the state of shellfish in the sound to their levels prior to development and industrialization. *Thus, in most cases we cannot distinguish whether 'stable' harvest rates represent stable natural populations or increased harvest effort on declining populations.* Changes in total harvest may reflect changes in effort or in regulations more than changes in populations.

Dungeness crab: *Cancer magister*

The commercial fishery for Dungeness crab uses baited crab pots, usually in <120 meters of water. In Puget Sound, the fishery is most productive in the northern waters (Figure 1), although the outer coast fishery is much larger. Dungeness crabs are also important recreationally; they are caught intertidally by hand or subtidally by crabpots, nets, or even hook-and-line.

Landings of Dungeness crab in Puget Sound have been highly variable from year to year, peaking at more than 2.3 million pounds in the late 1970s (Cheney and Mumford 1986), declining into the early 1980s, and then rising again (Figure 4). Tribal commercial harvest rose abruptly after 1994 following the Rafeedie court decision, so that total landings are now far higher than at any time in the past. Values of the annual catch remained <$4 million until 1994, and now are close to $15 million. Impacts of this increased harvest rate on long-term population viability are unknown, especially since factors causing bottlenecks of recruitment into the fishery have not been studied. Recreational harvest-

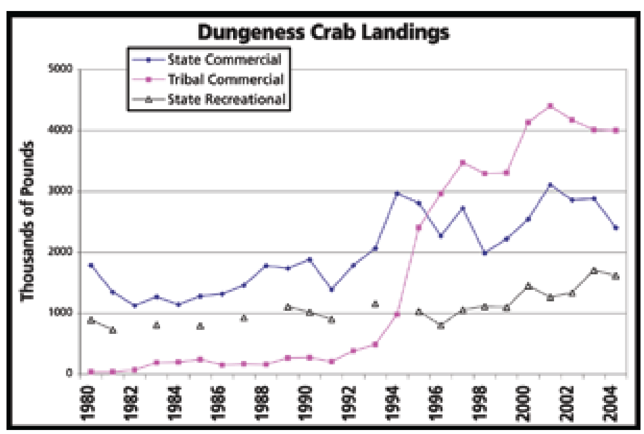

Figure 4. Commercial and recreational landings of Dungeness crab, including both tribal and non-tribal harvests. Unpublished data from WDFW.

ing is harder to quantify and estimates since 1980 have used several different methods, but clearly recreational harvesting of this resource is also substantial.

Native littleneck clams, *Protothaca staminea*, and other hardshell clams

Littleneck clams are exploited both commercially and recreationally and are now commonly farmed. Native littlenecks were (along with butter clams) the most important commercial shellfish in Puget Sound in the early 1900s. Populations declined with intensive exploitation in the 1930s, and recruitment of young was sometimes insufficient to replenish them (Chew and Ma 1987). Many tidelands were subsequently sold. Currently, Manila clams are increasing in economic importance (Figures 5 and 6) and have surpassed native littlenecks; they are the second-most important commercial clam species and a very popular recreational target. Price increases for littlenecks have made intensive culture techniques such as commercial 'seeding' and use of predator-exclusion nets economically viable in the last two decades. These culture techniques, in turn, allow more intense harvest rates. Farmed clams were worth $14 million in 2000 (PSAT 2003).

Commercial harvest of butter clams peaked at more than 0.5 million pounds a year in the early 1970s, then declined (Figure 5). This decline stems from several causes, including the increasing popularity of Manila clams. Other commercial competition came from increasing imports of eastern softshell clams and canned clams from Asia. In addition, mechanical dredging, a productive harvest method for butter clams, was banned in 1985.

Commercial harvests of other clams (excluding geoducks) are generally low at this time; both horse clams (*Tresus*) and softshell clams (*Mya*) were dredge-harvested in the late 1970s (up to 500,000 pounds per year), but this practice was discontinued in 1985 as noted previously. Current landings of *Tresus* are small (Figure 5), but there is still a significant commercial harvest of *Mya* (more than 500,000 lbs per year) from Puget Sound beaches.

Recreational harvests of native littleneck and butter clams as well as cockles and horse clams have all declined in recent years (Figure 6). These declines may simply be because harvesters are preferentially taking Manila clams instead, or they may reflect real declines in harvestable clams on popular beaches. The data do constitute a form of catch-per-unit-effort, since they are calculated as pounds taken per beach trip by recreational harvesters.

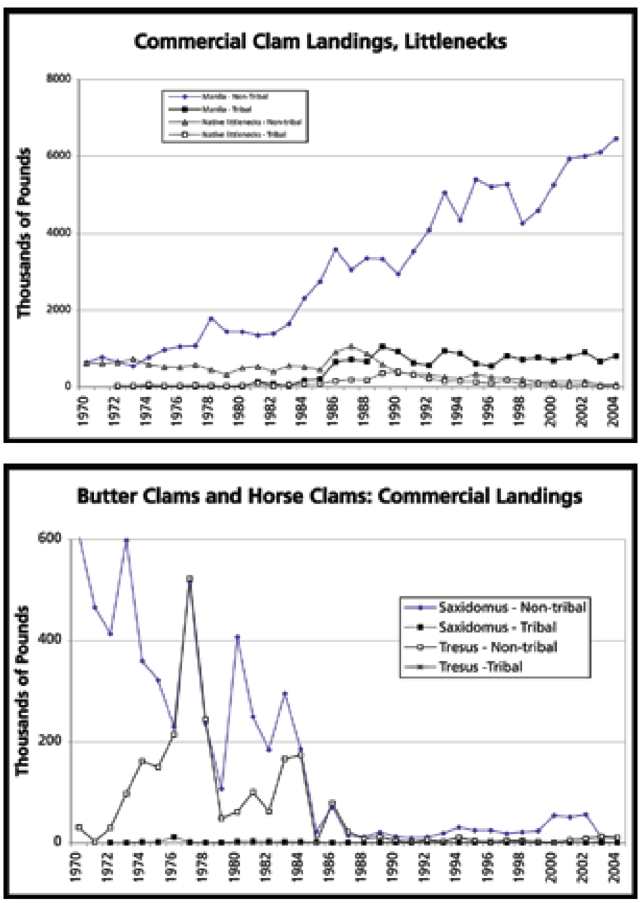

Figure 5. Commercial clam landings data from 1970 to present. Unpublished data from WDFW.

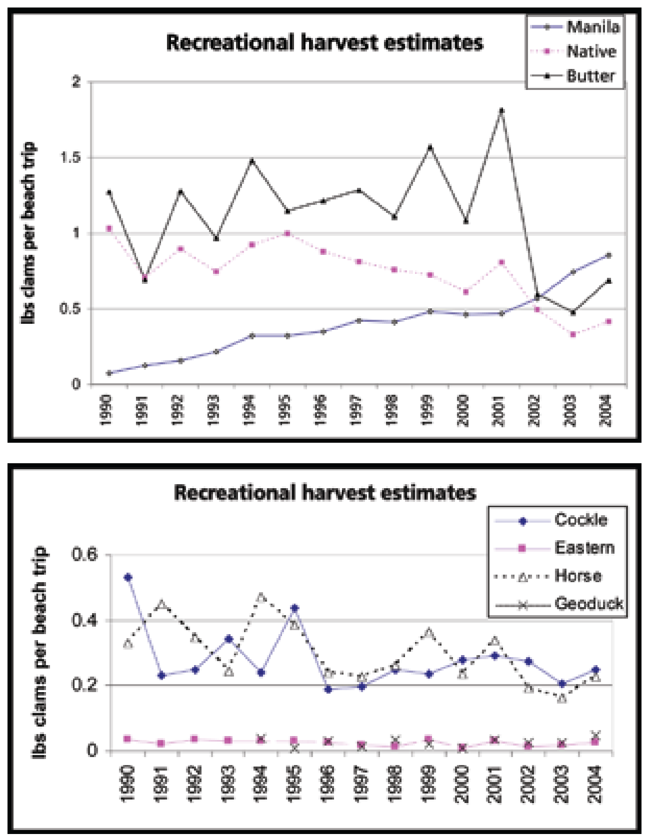

Figure 6. Recreational harvest estimates for a variety of clam species. Unpublished data from WDFW.

Geoduck clams: *Panopea generosa*

The commercial fishery for geoducks began in 1970. It is currently the largest and most valuable commercial native clam fishery on the Pacific coast, valued at approximately $20 million annually. Geoducks are harvested by divers using hand-held, high-pressure water jets in tracts leased from the state. The total weight of an individual may exceed 20 pounds, and they live to more than 100 years old. Older individuals are hard to harvest because they are at least 75 cm below the surface of the sediment. Commercial landings of geoducks have varied greatly over the last several decades (Figure 7), with changing regulations about allowable harvest areas, sizes, and harvestable proportion of the population. Before 1994, all the commercial landings were state harvest; after that time (especially from 1996 onwards), the state and tribes have used their equal shares of the commercially harvestable quota. Recreational harvests of geoducks are very small compared with other clams (Figure 6); their sparse intertidal populations and difficulty of hand-harvest make them a less-preferred target. Recently, price increases for geoducks have made intensive aquaculture economically viable; techniques include raising young clams from hatchery seed in PVC tubes in the intertidal zone on both state and private lands. These improvements in aquaculture methods have led to the beginning of a shift from wild harvest to culture (R. Shuman, B. Sizemore, pers. comm.).

In an attempt to ensure sustainability of the fishery, harvest is limited to approximately 2.7 percent of the available biomass (WDNR 2005). WDFW attempts to make estimates of available biomass, and their data suggest a relatively stable population (B. Sizemore, WDFW, unpubl. data). However, studies of age-frequency distributions and rates of natural mortality suggest that larval recruitment rates have been declining for decades, for unknown reasons (Orensanz et al. 2000). Recruitment appears to be relatively high in some regions but low elsewhere (M. McHugh, Tulalip Tribes, pers. comm.). Back-calculations suggest that current geoduck abundance in Puget Sound may be only 40-50 percent of its level during the 1930s (Orensanz et al. 2000). Some data also suggest that when geoduck densities become low, successful reproduction and recruitment may both decline further because of decreased fertilization and settlement in sparse aggregations (reviewed in Orensanz et al. 2000).

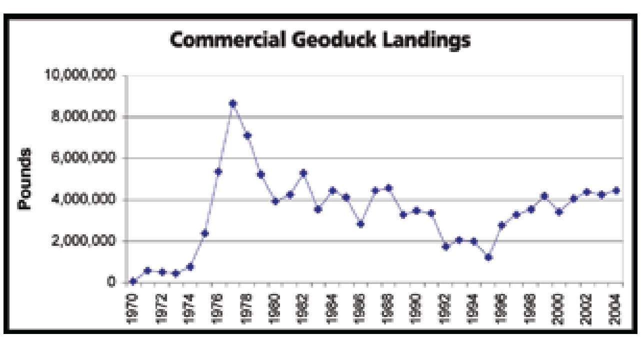

Figure 7. Commercial harvest levels (state plus tribal) for geoduck clams. Unpublished data from WDFW.

Native Olympia oysters: *Ostreola conchaphila (= Ostrea lurida)*

Olympia oysters have been commercially exploited since the1850s and commercially cultured since the1890s. Diked oyster beds were built in the intertidal zone beginning in the early 1900s. Despite culturing, production of Olympia oysters declined gradually after the turn of the century and is currently almost non-existent (Figure 8). Declines are attributed to initial overharvesting (especially in the coastal estuaries), and more recently to siltation and domestic and industrial pollutants from urbanization of estuaries, especially in southern Puget Sound (Galtsoff 1930, Korringa 1976, reviewed in Armstrong et al. 1993). Discharges from pulp mills were particularly damaging to oyster populations in the early and mid 1900s, leading to stricter management of the discharges. Predators (drilling snails and flatworms) introduced with Pacific oysters also likely contributed to the declines. In addition, growing grounds previously used for Olympia oysters are now used for the introduced Pacific oysters, further reducing production (McKernan et al. 1949). However, there are currently a variety of projects attempting restoration of Olympia oysters in Puget Sound (Allen 2005), involving state and federal agencies, non-governmental organizations, and partnerships such as the Olympia Oyster Restoration Program.

The Pacific oyster was introduced to Washington in the early 1900s and is now well established, mostly in oyster farms in protected bays. It is Washington's most valuable shellfish resource, with farmed oyster sales worth almost $58 million in 2000 (PSAT 2003). Much oyster culture is done in Willapa Bay and Grays Harbor, but significant culture activity is found in south Puget Sound, Hood Canal, and other scattered bays in the region.

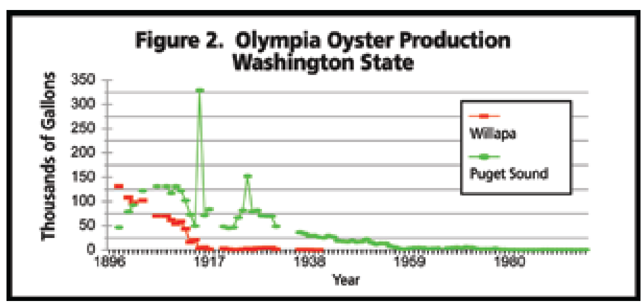

Figure 8. Olympic oyster productions in two regions of Washington state through time. From Cook et al. (2000)

Shellfish Harvest Areas: Status and Trends

As millions of people have moved into the Puget Sound area over the past century and a half, areas that were once relatively pristine are now heavily populated and developed, often making them unsuitable for shellfish harvesting (although not necessarily for the shellfish themselves). Pollutants, marine pathogens (e.g., *Vibrio parahaemolyticus*), and naturally occurring marine biotoxins (paralytic shellfish

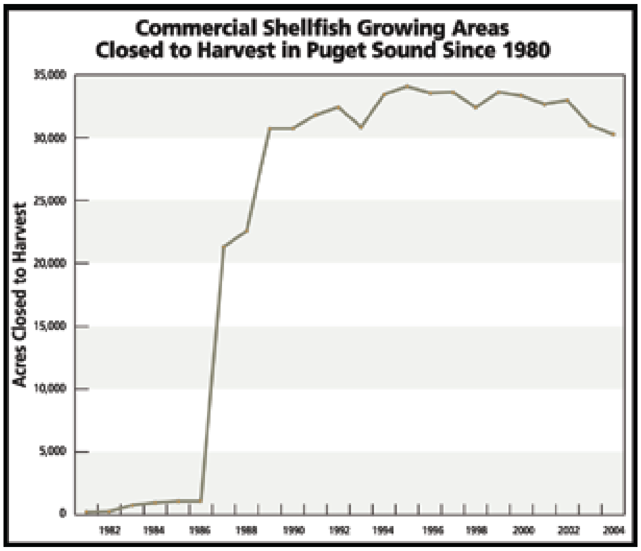

Figure 9. Acres of classified commercial shellfish growing areas closed to harvest because of pollution. PSAT (2004)

poison or domoic acid) can all restrict shellfish harvest opportunities. Bacterial counts are often used as an indicator for various pathogens, although bacteria themselves do not appear to harm shellfish. Since the mid-1980s, many commercial shellfish beds in Puget Sound have been forced to close because of pollution and more rigorous water quality monitoring. Nearly 20 percent of the sound's remaining shellfish areas have been closed since 1980 (Figure 9; PSAT 2004). Most of these closures occurred more than a decade ago. Closures have continued at a slower pace since the early 1990s. As a result of better pollution controls and related improvements in water quality, these closures have been offset by a nearly equivalent number of upgrades. Not illustrated here is the fact that the region's 'classified shellfish areas' are only a remnant of the area that was historically available for shellfish harvesting. For example, along the entire eastern shore of Puget Sound from Tacoma to Everett, commercial shellfish harvest is prohibited, and recreational harvest is ill-advised.

Most shellfish closures since 1980 have resulted not from industrial pollution or other point sources, but from diffuse nonpoint pollution such as failing onsite sewage systems, farm animal wastes, and stormwater runoff. The condition of shellfish growing areas generally reflects the surrounding land uses, pollution controls and watershed conditions (Glasoe et al. 2005). In 1997, the Washington Department of Health instituted an early warning system to identify emerging water quality problems in shellfish growing areas. Since the system's inception the number of commercial growing areas placed on the annual list has roughly doubled (PSAT 2004).

Ironically, some of the factors that reduce extraction of shellfish, such as local closing of commercial operations due to bacterial contamination, may actually benefit populations of native species because of reduced harvest pressure; the shellfish are not directly harmed by the bacteria. Other factors such as contaminants (e.g., pulp mill effluent), low dissolved oxygen, and high turbidity are harmful both to commercial efforts and to natural shellfish populations. The fact that harvest rates of many shellfish species are still rising despite harvestable area decreasing suggests that there is increasing pressure on shellfish beds that are still open for harvest, and on areas of commercial culture.

Human Effects on Habitat Attributes

While the species discussed above are diverse in their life histories, feeding modes, and exact habitat requirements, they share several susceptibilities to human impacts. Many of these impacts could be directly or indirectly reduced by restoration actions. In many cases the processes restored by one action would likely benefit a variety of shellfish species.

Direct loss of habitat

In urban areas (especially around Seattle, Tacoma, Everett and Bellingham), intertidal and shallow subtidal habitats that once supported shellfish populations have been completely lost. Construction of ports and commercial facilities often simply destroys habitat, especially soft-sediment and marsh areas. An estimated 4,800 acres have been lost because of such construction (Armstrong et al. 1993).

Alteration of substrate type

Any human impacts that alter sediment size or supply can reduce settlement, reduce growth, or outright kill many species of shellfish. In nature, each shellfish species is found most abundantly, or grows and reproduces most efficiently, in relatively specific types of substrates (data summarized in Appendix 1). However, experimental work is generally lacking on the specificity of substrate type required by each shellfish species. For Dungeness crabs, geoducks, oysters and cockles, preferred sediments are fairly fine sand or mud, often associated with eelgrass in shallower habitats. In contrast, most clams are most abundant in substrates with more of a gravel-sand sediment mixture. Increase in the abundance of very fine sediments (e.g., silt) can smother filter feeders (all but the crabs), either as adults or as newly settled juveniles. Several species have larvae that cannot settle or survive on very fine sediments; the common practice of 'graveling' fine-sediment shores to encourage the survival and growth of hardshell clams illustrates the importance of sediment type. On the other hand, loss of fine sediments from mixed substrates creates nearshore areas that are largely gravel and cobble, which are inappropriate habitats for any of these shellfish species (Dethier 1990). Human activities that affect nearshore sediment include dredging and filling, bulkheading, logging and log-rafting, and damming of rivers and streams. Many such impacts, however, can be mitigated and the underlying sediment-supply processes restored.

Pollution or other alterations in nearshore water characteristics

Shellfish are affected by the character and quality of nearshore waters both as larvae and as adults. Native shellfish species in Puget Sound spend as little as 11 days to as much as five months as larvae in the water column (Appendix 1). Larvae and juveniles of most marine organisms are more sensitive to physical conditions and to pollutants than are adults. These larvae require water that is relatively free of contaminants, of an appropriate temperature range, and with generally near-marine salinities (i.e., without too much variation in freshwater mixing). In addition, they require the natural currents that can transport them to nearshore areas appropriate for their settlement. Adult and juvenile shellfish likewise require water that is relatively free of toxic contaminants and has adequate levels of dissolved oxygen. Point-source pollution from chemical, industrial, and urban-related sources is still a major problem despite numerous regulations, and non-point pollution from non-urban areas is probably increasing.

Alteration of runoff from land and beach porewater

Newly settled clams of many types are very sensitive to their physical and chemical environment. Their early survival can be impacted by alterations in the conditions of water passing over or through beach sediments, such as in salinity, temperature, sediment load, or pollutants. These sorts of impacts can be readily altered through changes in upland development practices.

Changes in nearshore plankton

All the shellfish species discussed have larvae that feed in the water column; thus, to survive they require a predictable and non-toxic supply of plankton and edible detritus, and a minimal load of suspended sediment, which can clog their feeding structures. Adult shellfish (except for crabs) also require relatively predictable supplies of suspended food particles. Plankton quantity and type, i.e., the particular species that is predominant in the water column, can be dramatically affected by nutrient input into nearshore waters. Increased input of nitrogen, for instance, can cause plankton blooms, but not necessarily of the types that are consumed by shellfish. Toxic plankton blooms (e.g., those that cause paralytic shellfish poisoning) are clearly a problem even though they may not affect the shellfish themselves. Some data (Lassus et al. 1999) show that oyster growth can be negatively affected by toxic dinoflagellate blooms. It is hypothesized that some toxic plankton blooms could be caused by introduced plankton species, e.g., those transported in ballast water, although this has not been demonstrated (Woods Hole Oceanographic Institute 2005). The biological oxygen demand caused by dying plankton blooms also can kill many benthic organisms including crabs and clams because of the reduced oxygen levels in the water. A related, non-planktonic problem is harmful algal blooms of benthic algae, such as the increased prevalence of bladed green algae that may smother organisms beneath them (Nelson 2001, Nelson et al. 2003a, b). Such blooms may be caused by excess nutrients in the water column.

Introduced species

Introduced competitors (e.g. other bivalves) and predators (e.g., oyster drills) are another pathway for human effect on shellfish populations. Oyster drills have clearly had a negative impact on oyster populations, and there is concern about potential effects of European green crabs. High densities of introduced bivalves such as Manila clams may affect growth or recruitment of native shellfish, although this has not been demonstrated. In addition, habitat-altering introduced species such as cordgrass (*Spartina* spp.) or Japanese eelgrass (*Zostera japonica*) can cause dramatic changes to mudflats and other environments, making them uninhabitable for some former occupants.

Increased susceptibility to predators and parasites

Native shellfish are consumed as adults by both human and non-human predators, and as larvae by a different suite of planktonic predators. Direct human over-harvesting is clearly an impact of concern, but more subtle are changes in the natural environment that make shellfish more susceptible to other predators or parasites. These could include loss of eelgrass beds, which clearly shelter juvenile Dungeness crab and may provide nursery areas for other shellfish such as cockles; changes in surface sediments that make it easier for natural predators such as moonsnails and crabs to consume buried bivalves; and any change in the physical or chemical environment that causes physiological stress to organisms, which may make them more vulnerable to parasites or predators.

Nearshore aquaculture

Ironically, aquaculture operations for native or introduced shellfish species can constitute a stressor for natural shellfish populations in the nearshore. Many aquaculture techniques involve altering nearshore habitats, thus changing the environment for the native species. These alterations can include changing substrate types (e.g., adding gravel), extensively disturbing the sediment (e.g., to add geoduck spat or harvest adult shellfish), or making conditions less favorable for eelgrass growth (e.g., oyster aquaculture; Griffin 1997). Non-native shellfish compete with some native species for space in the sediment and planktonic food in the water column. In addition, their intensive culture has resulted in unintentional introductions of other non-native species that have had detrimental effects on the sound's ecology. However, both native and cultured non-native species benefit from good water quality, high primary and secondary productivity, and stable sediment characteristics. Similarly, poor conditions in the above parameters can harm both natives and non-natives. Thus, commercial aquaculture of non-native shellfish in Puget Sound has some direct negative effects on native shellfish but can have the positive effects of reducing harvest pressure on native species, creating a constituency for clean water, and helping to maintain and improve water quality.

Ecosystem Processes Supporting Habitat Attributes

A variety of natural processes in Puget Sound help maintain the conditions required by native shellfish species. Based on the discussion and data above, these include processes that support deposition of sand, mud, and gravel; maintain appropriate temperature, salinity, and turbidity; and produce phytoplankton and edible detritus. The PSNERP Conceptual Model of Puget Sound maps out connections between potential restoration actions, the restored processes, ecosystem structural elements that will change with altered processes, and ultimately restored functions of the ecosystem (e.g., shellfish production). Figure 10 explores several possible management measures or restoration actions and illustrates how altering key processes may affect shellfish populations. Restoring some habitat attributes for shellfish, such as the eelgrass beds used by juvenile crabs, requires restoring a different set of processes; these are explored in the Conceptual Model in the white paper on Eelgrass and Kelp. Note that there are constraints (listed at bottom) on improving the size and stability of shellfish populations that are unrelated to nearshore ecosystem processes.

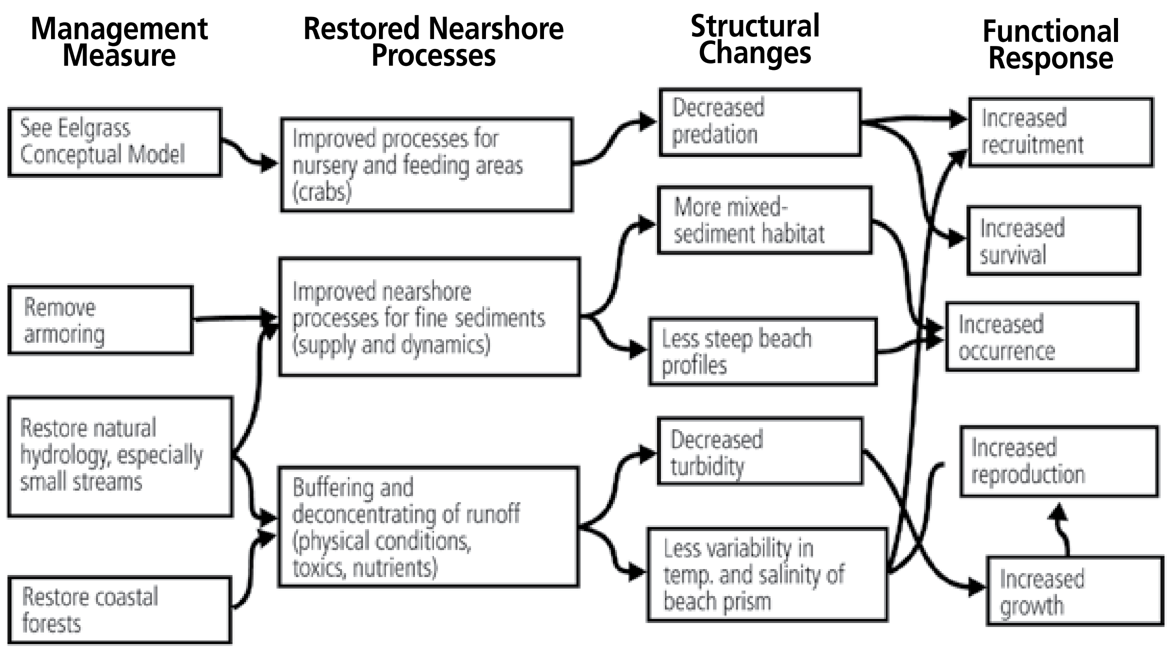

Figure 10. A conceptual model of the linkages between potential restoration actions and populations of native shellfish.

Critical Uncertainties

Although for all of the species discussed here we have good data on where they are found in nature, we cannot say with certainty that these habitats are the only (or even the best) ones for them. It is possible, for example, that "intertidal" clams live there simply because predators prevent their populations from thriving in the subtidal zone. Thus, we have correlations of species abundances with particular habitat types, but not definite cause-effect linkages. In a few cases, there are experimental data on tolerance of different conditions, such as salinities, that provide a clearer view of how constrained a species is to its 'normal' habitat.

More data on larval abundances and movements would be very useful in terms of learning about critical bottlenecks in this important life history phase, but such data are extremely difficult to obtain. For instance, it is possible that the abundances of hardshell clams and Dungeness crabs in southern Puget Sound could be limited by recruitment success. Is this the case? If so, is it because the larvae are not getting to the nearshore after dispersing for several weeks, or are they settling but then dying due to stressful physical conditions or abundant predators? Because this planktonic period is a 'black box', we cannot be certain that restoring nearshore habitat will necessarily result in improved populations of the target species.

With the exception of clear data on long-term population trends in Olympia oysters, we do not know to what extent shellfish populations have changed over time in Puget Sound. While recent harvest rates are known, we cannot use these data to estimate natural population levels or their trends. Thus, it is difficult to quantify the extent of the problem experienced by shellfish in the sound today, and it will be difficult to quantify improvements that might accompany restoration projects. Clearly, any projects designed to benefit this valued ecosystem component must be accompanied by monitoring of populations (in restored and control areas) to ascertain their effectiveness.

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Appendix 1. Habitat requirements for key shellfish species by life history stage

ND = no data. NR = not a relevant parameter for this organism. Where known, optimal values are given.

	Dungeness Crab			Littleneck Clam			Olympia Oyster			Geoduck		
Attribute	Larvae	Juveniles	Adults	Larvae	Juveniles	Adults	Larvae	Juveniles	Adults	Larvae	Juveniles	Adults
Tidal elevation/depth	pelagic, 3-5 months	low-mid intertidal	low intertidal to >100m	pelagic, 3 weeks	low-mid intertidal	mean lower low water	pelagic, 11-16 days	low intertidal and subtidal	0-10m deep	pelagic, 4-6 weeks	mostly subtidal	low intertidal to shallow subtidal
Salinity (ppt)	25-30	ND	saline	27-32	saline	24-31	ND	ND	>25	27-32	saline	>25
Temperature (°C)	10-14	ND	3-19	10-15	ND	12-18	ND	ND	ND	6-16	ND	<16
Dissolved Oxygen	high	high	high	high	high	high	high	high	high	high	high	high
Nutrients	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Wave exposure		low-med	low-med		moderate	moderate		low	low		moderate	moderate
Shipman shoretypes		bluffs, barrier beaches, estuarine deltas, estuaries, low-energy bays	bluffs, barrier beaches, estuarine deltas, estuaries, low-energy bays		bluffs, barrier beaches, estuarine deltas, estuaries	bluffs, barrier beaches, estuarine deltas, estuaries		estuarine deltas, estuaries, low-energy bays	estuarine deltas, estuaries, low-energy bays		bluffs, low-energy bays	bluffs, low-energy bays
Sediment grain size		sand-gravel	sand		gravel-sand	gravel-sand		mud + coarse	mud +coarse		mud or sand	mud or sand
Suspended sediment	low	low	low	low	low	low	low	low	low	low	low	low
Light penetration	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Food	plankton	molluscs, crustacea	clams, crustacea	plankton, detritus	plankton, detritus	plankton, detritus	plankton, detritus	plankton, detritus	plankton, detritus	plankton, detritus	plankton, detritus	plankton, detritus
Other elements		complex surface structure			surface gravel	surface gravel	stable settlement site			stable settlement site		

PSNERP and the Nearshore Partnership

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) was formally initiated as a General Investigation (GI) Feasibility Study in September 2001 through a cost-share agreement between the U.S. Army Corps of Engineers and the State of Washington, represented by the Washington Department of Fish and Wildlife. This agreement describes our joint interests and responsibilities to complete a feasibility study to

"*…evaluate significant ecosystem degradation in the Puget Sound Basin; to formulate, evaluate, and screen potential solutions to these problems; and to recommend a series of actions and projects that have a federal interest and are supported by a local entity willing to provide the necessary items of local cooperation.*"

The current Work Plan describing our approach to completing this study can be found at:

http://pugetsoundnearshore.org/documents/StrategicWork-Planfinal.pdf

Since that time, PSNERP has attracted considerable attention and support from a diverse group of individuals and organizations interested and involved in improving the health of Puget Sound nearshore ecosystems and the biological, cultural, and economic resources they support. The **Puget Sound Nearshore Partnership** is the name we have chosen to describe this growing and diverse group, and the work we will collectively undertake that ultimately supports the goals of PSNERP, but is beyond the scope of the GI Study. Collaborating with the Puget Sound Action Team, the Nearshore Partnership seeks to implement portions of their Work Plan pertaining to nearshore habitat restoration issues. We understand that the mission of PSNERP remains at the core of our partnership. However, restoration projects, information transfer, scientific studies, and other activities can and should occur to advance our understanding and, ultimately, the health of the Puget Sound nearshore beyond the original focus and scope of the ongoing GI Study.

As of the date of publication for this Technical Report, our partnership includes participation by the following entities:

- King Conservation District
- King County
- National Wildlife Federation
- NOAA Fisheries
- NOAA Restoration Center
- Northwest Indian Fisheries Commission
- Northwest Straits Commission
- People for Puget Sound
- Pierce County
- Puget Sound Partnership
- Recreation and Conservation Office
- Salmon Recovery Funding Board
- Taylor Shellfish Company
- The Nature Conservancy
- U.S. Army Corps of Engineers
- U.S. Department of Energy
- U.S. Environmental Protection Agency
- U.S. Geological Survey
- U.S. Fish and Wildlife Service
- U.S. Navy
- University of Washington
- Washington Department of Ecology
- Washington Department of Fish and Wildlife
- Washington Department of Natural Resources
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