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MUSSEL AQUACULTURE IN PUGET SOUND

TECHNICAL REPORT

Mussel Aquaculture in Puget Sound

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Washington Sea Grant Program
University of Washington • Seattle

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Cover photo of Race Lagoon mussels by Roger Schreiber

Key Words 1. Mussels 2. Aquaculture—Mussels

This research and this publication were supported by grant NA84AA-D-11, projects R/A-16 and A/PC-5, from the National Oceanic and Atmospheric Administration to the Washington Sea Grant Program.

Copies of this report may be obtained from Washington Sea Grant Communications, College of Ocean and Fishery Sciences, University of Washington, Seattle, WA 98195.

Washington Sea Grant Program
College of Ocean and Fishery Sciences
University of Washington HG-30
Seattle, WA 98195

WSG 85-4
October 1985
$5.00

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PREFACE

Culturing economically important marine organisms is becoming more prevalent worldwide. One animal which has experienced vast utilization in marine aquaculture is the mussel. *Mytilus edulis*, the bay mussel, is found worldwide and is the predominant species cultured for human consumption, though several other species are used as well. In the Pacific Northwest a new aquaculture industry is emerging that is producing high quality mussels—again, *Mytilus edulis* is the common species used.

The intent of this paper is to describe types of mussel aquaculture used around the world and the evolution of mussel aquaculture in the Pacific Northwest. In addition, this report will present information concerning mussel aquaculture in Puget Sound that has been the result of ten years of research by students and faculty of the School of Fisheries in the College of Ocean and Fishery Sciences, University of Washington. We hope this publication will be of value to existing and future mussel aquaculturists in Puget Sound.

Douglas Skidmore and Kenneth K. Chew
February 1985

Acknowledgments

This report would not have been possible without the financial support of the Washington Sea Grant Program and the Pacific Coast Oyster Growers Association.

The authors wish to acknowledge several people and organizations who have contributed greatly to this publication. Special thanks is extended to Linda Chaves-Michael, Paul Waterstrat, Kurt Johnson and Katherine Falmagne-Kinchea, who each worked on graduate degrees in the School of Fisheries and whose thesis research on mussels provided the data base for the preparation of this technical report. Further, we especially want to acknowledge individuals such as Pam Sparks, Louisa Nishitani, J.H. Beattie, and Clarke Beaudry for their assistance in the laboratory, field sampling, processing and reviewing of various portions of this document. Charles D. Magoon of the Washington State Department of Natural Resources was most helpful in lending assistance to the sampling at stations in southern Puget Sound.

We also want to acknowledge Peter Jefferds of Penn Cove Mussels for his continued support of the projects, for work with graduate students, and for consultation to the Washington Sea Grant Program.

Various state agencies have contributed to making the mussel culture program through Washington Sea Grant a success. The Washington State Department of Fisheries have supported Washington Sea Grant mussel studies since its inception and provided resources to expand some of the studies. The National Marine Fisheries Service of National Oceanic and Atmospheric Administration of the U.S. Department of Commerce and the Environmental Protection Agency have been extremely helpful in providing facilities for our experimental shellfish hatchery and aquaculture site located in Clam Bay near the town of Manchester. This facility was a pivotal point to many of our field operations and attempts made in spawning and culturing the blue and California mussels. Further, the Washington State Department of Natural Resources was most helpful in providing laboratory and dock facilities at the Budd Inlet experimental site in southern Puget Sound.

Special thanks goes to Vicki Miles, designer for the Washington Sea Grant Program at the University of Washington for her efforts in providing many of the illustrations.

Finally, the authors wish to especially thank Andrea Jarvela Corell for her editorial assistance in the preparation of this important document on mussel culture for the State of Washington.

1 GROWING MUSSELS

On a global scale, the production of economically important marine organisms is increasing. High quality seafood and saleable marine products of many kinds are being planted, raised, and harvested from the world's oceans. In some countries great emphasis has been placed on utilizing space in the sea for culturing marine organisms. Mussels are farmed in The Netherlands, France, Germany, Wales, Spain, Norway, Italy, Yugoslavia, U.S.S.R., India, China, Korea, The Philippines, Venezuela, Canada, New Zealand, Mexico, and the United States (Korringa, 1976; Lutz, 1980; Chew, 1984; Myers, 1981; Jenkins, 1979; see Table 1 for production figures).

Mussels have been cultured in countries such as France and The Netherlands for several hundred years (Mason, 1971). Other countries have only recently begun mussel cul-

Table 1. Top ten mussel producing nations, species grown and culture technique used. Numbers in thousands of metric tons.[1]

Country	1979	1980	1981
Netherlands	97.4	76.9	109.4
Spain	78.4	95.7	93.5
France	61.9	74.9	80.5
Denmark	56.7	90.4	79.0
Korea	96.1	70.4	78.3
China	65.9	67.2	74.8
Thailand	64.8	40.5	36.7
Chile	18.4	22.2	16.2
USSR	13.4	14.2	14.7
Peru	13.2	13.8	14.0

	Species	Culture technique
Netherlands	*Mytilus edulis*	Bottom culture
Spain	*Mytilus edulis*	Raft culture
France	*Mytius edulis*	Bouchot culture
Denmark	*Mytilus edulis*	Bottom culture
Korea	*Mytilus crassitesta*	Longline
China	*Mytilus edulis* *Mytilus viridis* *Mytilus smaragdinus*	Longline, rafts
Thailand	*Mytilus smaragdinus* *Modiolus* spp.	Rafts
Chile	*Mytilus chilensis*, *Aulacomya ater*	
USSR	*Mytilus galloprovincialis*	
Peru	*Aulacomya ater*	

[1] World Production of mussels in 1981 was 653 thousand metric tons ~ 1.5 billion lbs.

Source: Food and Agricultural Organization of the United Nations, Yearbook of Fishery Statistics, catches and landings, volume 52.

ture: raft culture of mussels began in Spain within the last 35 years (Korringa, 1976), the first mussel farms in the United States were established in the early 1970s in Maine (Abandoned Farms) and in Puget Sound (Penn Cove Mussels). Since that time the production of mussels on both coasts has increased and several more companies are now in operation.

Sales of cultured and wild harvest mussels in the Pacific Northwest have steadily increased since 1974 (Figure 1). Increased sales are a response to increasing demand for high quality shellfish in local restaurants. Many of the finest restaurants in the Pacific Northwest commonly serve mussels as appetizers or as main entrees. The most common way they are prepared is steamed in a wine and herb sauce.

Popularity of mussels in the Northwest has increased due to the high quality of local cultured mussels. Locally grown mussels have been entered in two national mussel tasting contests and Washington cultured mussels from Penn Cove have won both competitions (*Ocean Leader*, 1981). Washington mussels held two of the top three positions in both competitions.

Most domestic mussels now sold in the United States come from a single major East Coast producer, Great Eastern Mussel Farms, Inc. in Tenants Harbor, Maine. Great Eastern dredges wild and cultured mussels from the sea bottom. Once ashore the mussels are taken to a processing plant where they are held in large seawater tanks. Processing is similar to methods used in the Netherlands (see *Techniques to Grow Mussels*). Clumps are separated and washed by machine and sorted by hand on a conveyor.

The University of Washington began investigating mussel culture in 1973. This coincided with the establishment of the first mussel farm in Puget Sound by Peter Jefferds. Washington Sea Grant support enabled the School of Fisheries, University of Washington, to investigate the potential of mussel aquaculture in Puget Sound. The approach was to determine where mussels could survive and grow in Puget Sound at a rate which could support viable commercial ventures.

Several key parameters had to be addressed in the investigations. Wild seed sources have been used by all mussel farms throughout the world, but the ability to catch adequate amounts of seed in Puget Sound had to be established. In addition, the growth rates of mussels in Puget Sound needed to be determined and compared to other areas of the world. Primary efforts were directed toward finding areas where adequate seed could be caught and determining whether it was feasible to produce seed in hatcheries. Growth and mortality rates were recorded for many areas of Puget Sound. High mortality rates of *Mytilus edulis* in some areas prompted research on the aquaculture potential of another mussel species, *Mytilus californianus*. The results of these investigations are presented in this report, along with a review of the different methods used to grow mussels in various regions of the world.

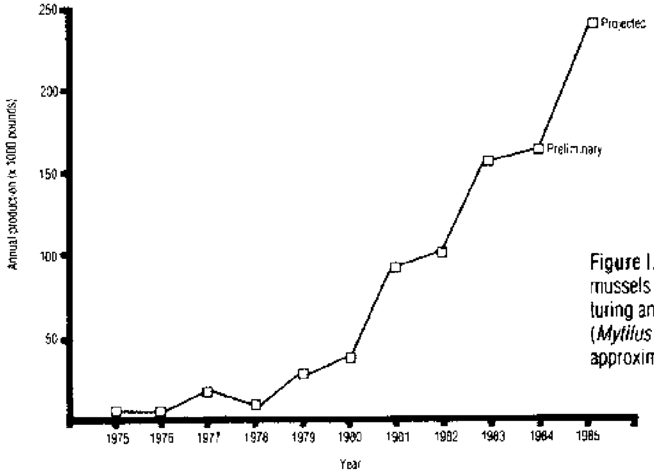


Figure I. Annual production of mussels in Washington State. Culturing and harvesting of mussels (*Mytilus edulis*) did not begin until approximately 1974.

Mussel farming has been practiced in some European countries for 700 years, but only since the 1970s in North America (Mason, 1971). The principle species of mussel cultured has been *Mytilus edulis L.*, the common bay or blue mussel. Over the years, techniques to grow mussels have evolved into three basic forms: seabottom culture, bouchots (or intertidal culture), and raft and longline culture. Methods differ because they evolved out of the necessity to comply with differing environmental conditions between regions. Bottom culture can be more successful under a specific situation than bouchots or raft culture and vice versa. (For additional information, see the following publications: Korringa, 1976; Lutz, 1974 and 1980; Jenkins, 1979; Myers, 1981; Mason, 1976; Lutz et al., 1977; Loosanoff, 1943.) Some of these techniques will be summarized and their potential application in Puget Sound discussed in this chapter.

Seabottom Culture

Mussel farmers in The Netherlands and Germany have successfully used bottom culture techniques for 300 years to produce millions of kilograms of mussels to supply their own country as well as parts of France and Belgium (Lutz, 1980). The Netherlands government leases plots of bottom land (500 x 200 meters; 24 acres) in the shallows of the Zeeland and Waddenzee estuaries for a reasonable fee. Seed mussels are placed on the plots of land and grow to market size in 20 months. The annual harvest from The Netherlands has been in excess of 100,000 metric tons of live mussels, although it has been decreasing in recent years.

Bottom culture of mussels is now being tried on the northeast coast of the United States. Natural subtidal beds have been harvested for several years, but stock enhancement by planting seed may sustain the harvest of mussels in that area.

Seed Collection

Almost every year a natural settlement of small mussels occurs in certain regions of The Netherlands. It is this abundant natural set of seed mussels which makes this productive industry possible. Seed beds are controlled by the Ministry and, on the advice of officials, are opened in the late spring or summer. Seed mussels are removed from the public beds by large dredging boats or by hand with special forks. They are generally collected and relayed onto growing plots when they are about the size of a grain of wheat or slightly larger.

Densities

Seed mussels are spread on the sea bottom to obtain a final harvest density of no more than eight kilograms of marketable mussels per square meter (approximately 15 pounds per square yard or 1.6 pounds per square foot). At densities greater than this, slower growth and an inferior mussel will result. To obtain the proper growth densities, the following measurements are used when seed is spread (Korringa, 1976):

1. Wheat grain-sized seed mussels (0.5–0.75 centimeters)
   Density: 20 metric tons per hectare (approximately 18,000 pounds per acre or 0.4 pounds per square foot).
2. Bean-sized seed mussels (approximately one centimeter)
   Density: 30–35 metric tons per hectare (approximately 27,000 pounds per acre or 0.6 pounds per square foot).

Substrates

Plots of land leased to farmers are generally subtidal (below low water). The plots range from two to seven meters below low water. Growing plots are almost never seen above water and must be worked by boats with special dredges to maintain the plots. The bottom is probed with special sticks to reveal the texture of the substrate. Substrate that is too muddy or too sandy is undesirable for maximum growth: an even mixture of mud and sand is optimal.

Cleansing

During harvesting, silt that is stirred up by the dredge is ingested by the mussels and retained between its valves. To remedy this problem before processing and marketing, mussels are taken to a cleansing area of intertidal water with a hard sandy bottom where they are left to eject the grit. This cleansing period—about three to eight days—also allows seagulls to perform a free service of removing any starfish and dead or dying mussels during low tide.

Washing and Packing

After being dredged off the cleansing plot, mussels are taken to the processing plant where a special machine separates, washes, and packs them at a rate of two to four tons per hour (Korringa, 1976). The machine (Figure 2), which requires seven men to operate it, has six stations that the mussels proceed through:

1. Hopper—mussels are introduced to the hopper by either conveyer belts or grabs
2. Breaker—a rotating shaft with off-set pairs of blades every several inches. The shaft turns at approximately 34 rpm when the tube is tightly filled with mussels and water.
3. Washer—a rotating cylinder constucted of steel rings, placed so that no mussels fall through. It is angled at 10° so that the mussels flow through slowly as they are washed by seawater pumped through perforated tubes.
4. Blower—mussels drop onto a wire netting that moves over an upward air current which eliminates empty shells, leaves, or seaweed such as *Ulva*.
5. Sorter—mussels drop from the blower to a rubber sorting belt. Four or five men stand alongside and pick out undesirable objects.
6. Weighing apparatus—clean mussels are fed into a hopper, which automatically weighs them. They are then bagged by another worker.

Problems

Shortage of Seed An average of one out of five years has a failure of seed.

Predators Crabs and starfish can consume large amounts of mussels.

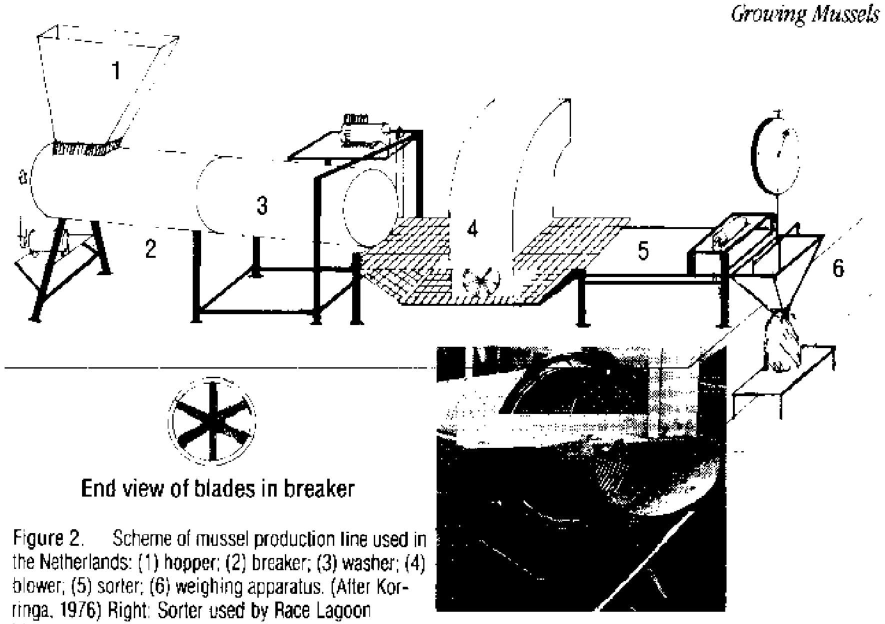


Figure 2. Scheme of mussel production line used in the Netherlands: (1) hopper; (2) breaker; (3) washer; (4) blower; (5) sorter; (6) weighing apparatus. (After Korringa, 1976) Right: Sorter used by Race Lagoon Mussels.

Weather Waves and currents can be the deadliest enemy. Mussel plots are generally located in protected waters; however, at times winter storms and ice are problems to contend with.

Freshwater An influx of freshwater that causes a substantial drop in salinity can cause mass mortalities of mussels.

Silt Mussels produce silt by their own filtering activity, but if the substrate is too silty the mussels cannot stay above the surface of the mud and may smother. If silt is deposited under the mussels they will try to stay above it, but they will still be vulnerable to erosion during strong tidal movements. Farmers in The Netherlands sometimes remove the mussels and tow a chain-harrow across their beds to alleviate this problem.

Barnacles When barnacles are attached to mussels, they are harder to clean and fetch a lower price at market.

Potential of Seabottom Culture in Puget Sound

Seabottom culture of mussels probably has the least potential application for use in Puget Sound. No subtidal beds of *Mytilus edulis* are known to exist in Puget Sound, but they are abundant subtidally along the northeast coast of the United States. Large subtidal mussel beds are found off the coasts of Maine, New Hampshire, and Massachusetts. These beds are harvested with dredges and millions of pounds of mussels are shipped throughout the United States. These beds are reseeded and managed like mussel beds in The Netherlands.

Growing mussels subtidally is an unlikely prospect in Puget Sound, primarily because of predation. Starfish and crabs are abundant and consume any mussels or other shellfish that happen to appear in the subtidal zone. Evidence of this occurred when several ropes with harvest-sized mussels were inadvertently dropped to the bottom of Penn Cove. When retrieved several weeks later, the lines of mussels had been almost entirely consumed by starfish. Evidence of crabs eating the mussels could also be detected. Many of the shells were broken, indicating that crabs had broken them and devoured the meat inside. Any attempt to grow mussels subtidally would require control of predators by fencing or elimination, a seemingly difficult prospect at best.

Bouchot and Intertidal Culture

Along the southern coast of France and in parts of the northern coastline of Normandy and Brittany, mussel culture has been conducted on stakes or poles called *bouchots*. Bouchot farming originated in the Anse de l'Aiguillon, on the coast of France, in 1235. A shipwrecked Irishman, Patrick Walton, placed poles with net strung on them in an attempt to catch seabirds for food (Mason, 1971). Not many birds were captured, but mussels grew profusely on the poles. Since then this method has changed little. Space for the bouchot poles are leased by the French State for 25-year periods. France produces over 50,000 metric tons of live mussels annually, and all are sold fresh. There are over 1,100 kilometers (700 miles) of rows of mussel poles along the French coast.

Seed Collection

Seed mussels for bouchots are collected on bouchot poles or on racks with coco-fiber lines. Poles are placed in deeper areas than the growing sites. The poles are planted low intertidally in January–April to allow the growth of hydroids and other highly desirable "hairy" textured plants and organisms that attract mussel larvae. The larvae settle in May–June and grow rapidly.

A more recent seed collection method is racks made to hold coco-fiber strands off the bottom. Coco-fiber has the correct texture to induce settlement of mussel larvae earlier than the poles. Seed is also more easily transported on ropes than on poles. Racks are made of poles placed in rows 1.5 meters apart and spaced in 2.4-meter intervals. Coco-fiber is laid the length of the rows over two levels of cross bars, one 60 centimeters off the bottom and the other 95 centimeters (Figure 3). The rows are generally 25 meters long and contain 25 strands per level. The seed racks are placed relatively low in the intertidal area compared to the growing areas.

Transferring Mussel Seed to Higher Ground

After the seed reaches a size of approximately 20 millimeters, it is harvested from the poles and packed in nylon tube netting called "boudins." The netting ends up resembling a sausage and is approximately five meters long and ten centimeters thick. In turn, each is wrapped spirally around the pole, leaving space between the wraps, giving it a candy cane stripe appearance. The extra space allows the mussels room to grow, so thinning may be unnecessary. This process is shown in Figure 4.

Ropes ladened with seed from the rack collectors are transferred in July to growing areas. The coco-fiber rope is cut into sections 2.5–3 meters long, and because of the high density of seed on them, only one section is used for each pole. Cut sections are wrapped on bare poles and left to grow.

Construction

Bouchot poles are placed in rows 50 meters long and aligned perpendicular to the coastline. A bouchot (a row of poles) can be either a single row or double row. In single rows, the poles are placed about 20 centimeters apart and contain 125 poles in a row. Double-rowed bouchots have two 190-pole rows, one meter apart, with poles spaced at 32-centimeter intervals. Bouchot rows should be spaced 25 meters from one another but are often only 15–20 meters apart (Korringa, 1976).

Oak poles are used almost exclusively, and they are generally 4–6 meters long and 12–20 centimeters in diameter at the thick end. Poles are placed by drilling a hole in the mud with an auger on a tractor. The pole is then inserted into the hole 2–3 meters deep. The top 1.5 meters of pole is covered with mussels and the lower portion is sometimes wrapped with plastic to deter starfish.

Tides, Temperatures, and Salinities

Bouchots are located on the shallow, gentle sloping shelves of the Pertuis Breton region of the Atlantic coast of France. The tidal range varies from five meters during spring tides to two meters during neap tides. Current velocities can reach two to three knots on spring ebbs. Water temperatures range from about 8°C–20°C in the westernmost section. Salinities vary little and remain in the range of 32–35 parts per thousand.

Harvesting

The harvest season is from May 1–February 1, and all harvesting is done by tractors with special attachments to scrape off the mussels. Grading of mussels occurs aboard a large

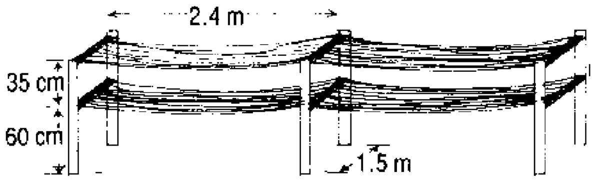


Figure 3. Rack for seed collection.

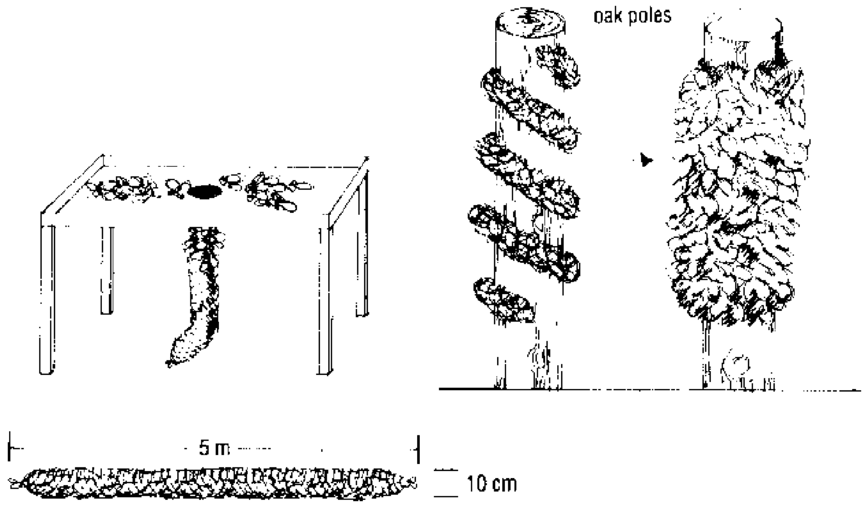


Figure 4. Making of "boudin" seed sausages, which are wrapped spirally around bouchot poles. Mussels will eventually grow out of the mesh and cover the poles.

boat, where mussels are placed on a trellis to be scrubbed and washed. Workers wear thick gloves to hand scrub the mussels over the trellis, then wash them with jets of water to separate them and rinse off any grit. The smaller ones are separated out and are eventually placed back in tube netting to be wrapped back on growing poles.

Problems

Weather Gales may occur, and sometimes can damage the mussel poles, especially those that have been weakened by the work of shipworms.

Predators Though starfish are only a slight problem in the intertidal area, stingrays move in during the summer months and consume the mussels. This problem is so severe that large mesh nets are strung on the outside of the growing areas each year to deter the predators.

Shipworms The poles used to build the bouchots system are made of wood and are therefore susceptible to becoming honeycombed and weakened by shipworms. Life expectancy of poles is from 5–6 years.

Considerations of Bouchot or Intertidal Culture in Puget Sound

Mussels grown on bouchots in France are renowned for their high quality, and fetch a higher price than raft grown mussels from Spain (Korringa, 1976). Because mussels are grown intertidally with daily exposure to air, the shelf life of the product is enhanced and the mussels have a somewhat different flavor and texture than those grown on rafts or longlines, which are continuously immersed. The ability of the mussel to develop a tougher shell and remain closed when out of water is an adaption which increases its shelf life in the market.

Intertidal culture using bouchots or other types of intertidal formations could be initiated in Puget Sound, but there are problems that may be encountered in growing mussels intertidally here. Unlike some parts of France, where barnacles are not much of a problem, barnacle settlements in Puget Sound are substantial, and those that settle and grow on mussels must be removed before the mussels can be marketed. This is generally done by hand and is very time consuming. Barnacles on intertidal mussels are especially difficult in that they develop a harder, thicker shell than do those on subtidal mussels. In addition, the growth rate of mussels grown intertidally is usually slower than mussels grown on rafts or longlines because exposure to the air at low tide reduces feeding time.

Intertidal Culture Methods Used in Puget Sound

Only one commercial mussel farm in Puget Sound has based its operation in the intertidal zone. Race Lagoon Mussels, a company located on Saratoga Passage on the east side of Whidbey Island at Race Lagoon uses an intertidal longline system to grow mussels. This system is much like the system used to grow oysters in Grays Harbor, Washington. Because the system is located on a beach between the high tide and low tide water level, it can only be maintained on tides that are low enough to expose it.

The intertidal longline used at Race Lagoon consists of 100-foot lines that are staked to the beach and supported off the beach with plastic PVC pipe. The pipes are inserted into the beach in rows that consist of ten support pipes spaced approximately nine feet apart. The rows are placed three feet apart and parallel to the shoreline. Mussels are grown at tide levels ranging from three feet to minus two feet MLLW (Figure 5).

Seed mussels placed in this system for growout are procured in two ways. Seed is either caught on lines or placed in mesh tubing. Seed caught on lines is collected in a similar fashion as mentioned earlier in this section and seen in Figure 3. One-hundred-foot lines are strung on racks in the early spring to catch the set in May or June. The seed lines incorporate the same coconut fibre twine that the French use to catch mussel larvae. Coconut fibre twine (coir) attracts mussel larvae because of its fibrous texture. Larval mussels seek a small niche in which to hide and coir offers such spaces. Seed collected from rocks, pilings, and excess from harvest are placed in mesh tubes 100 feet long (Figure 4). In both cases the seed lines are stretched out into the rows of pipes and placed into position.

When mussels reach harvest size, the lines are removed from the pipes and a buoy is attached to one end. At high tide the lines are pulled into a boat and taken to a cleaning barge. The mussels are removed from the lines, separated, graded, washed, and bagged.

Raft Culture

Using Spain as an example, rafts initially were constructed of old hulls of fishing vessels. Timbers were used to build a platform radiating horizontally from the hull for hanging mussel lines (Lutz, 1980). These lines were used to catch mussel seed as well as grow them to harvest size. More sophisticated float design construction has been used in the past ten years.

Culturing of mussels is prevalent in the protected waters of Spain's *Rias*. Until 1974, Spain was the world's largest producer of mussels, with annual sales of 130,000 metric tons (Lutz, 1980). However, with the addition of 3,000 additional rafts, the Rias became overcrowded and production dropped to 50,000 metric tons per year. Mussel production remained depressed until 1980, when production increased to nearly 100,000 metric tons per year (FAO, 1983).

The use of rafts for growing mussels is now widespread, though the technology of raft construction has changed dramatically with the development of cost-effective floats and gear. Rafts are now used in the United States, Sweden, New Zealand, Italy, and many other countries. The methods used in Spain are presented here as an example of mussel culture using rafts.

Figure 5. Intertidal longline system used at Race Lagoon.

Seed Collection

Mussel larvae settle in abundance on the rocks of the intertidal zone in Spain. Every year seed mussels are scraped off these rocks, providing the Spanish mussel industry with 60–70 percent of its needed seed (Korringa, 1976). During seed collection season small boats are used to transport workers and seed. On an average tide, several workers can gather 1,500 kilograms of seed. The farmers either collect the seed themselves or buy it, which is sometimes cheaper than hiring people to collect it.

The remaining portion of seed is collected directly on ropes suspended from rafts. Ropes are hung from rafts from December through January to catch seed during February and March. In the Pacific Northwest, mussel seed generally is caught in late April to early June.

Attaching Seed to Ropes

Seed is collected when it is from 8–10 millimeters long. The seed mussels are then attached to the ropes with a bandage-like tissue made especially for the mussel industry (Figure 6). The bandage is wrapped around the rope while the mussels are placed in position. The mussels attach to the rope in a few days and the rayon bandage dissolves.

It takes approximately 6–7 minutes for an experienced worker to load a single eight-meter rope. Ropes are made from esparto grass, old trawl nets, or synthetics (most are synthetic rope). Seed mussels reach market size (shell length of 80–100 millimeters) in 12–18 months, and each eight- to nine-meter rope can yield 250 pounds (113 kilograms) of live marketable mussels. Annually, a raft will yield 175,000 pounds utilizing 700 ropes (Korringa, 1976; Lutz, 1980).

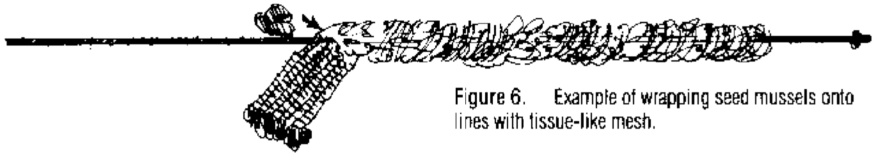


Figure 6. Example of wrapping seed mussels onto lines with tissue-like mesh.

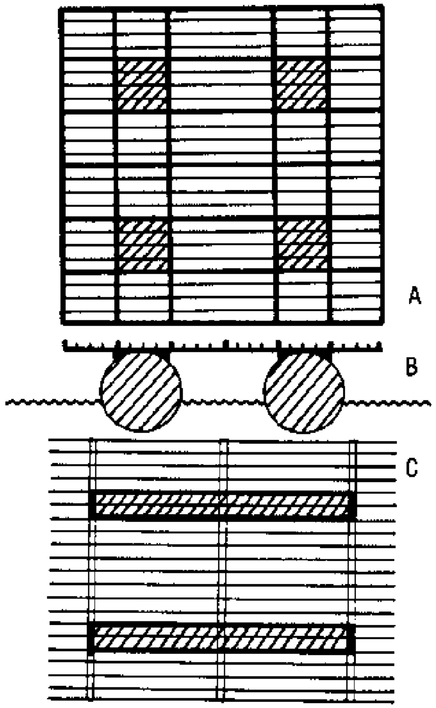


Figure 7. Raft construction: a) cubical floatation, wooden framework, used in Spain; b) steel ball floation, wooden framework; c) styrofoam floats attached with steel "box" beams and pealed poles as cross members (used by Penn Cove Mussels Inc.).

Raft Configurations

An average-sized raft is about 23 meters square and is anchored in at least 11 meters of water at low tide. Culture lines are approximately nine meters long, so they never touch the bottom. Rafts are made as simple as possible: concrete or steel floats have been used, and even styrofoam and fiberglass are being tested (Lutz, 1980). In Spain a wooden eucalyptus framework of five-centimeter-square timbers is used to support ropes. The timbers are placed 45 centimeters apart and ropes are hung from them (Figure 7).

Thinning

After three or four months, mussels can become overcrowded, which can reduce growth or cause layers to separate from the rope and fall off. Before this occurs the mussels are partially stripped off the lines and the excess is wrapped onto new lines. One rope may sometimes produce three or four new ones.

Depuration

To be sold fresh in Spain or exported to France, mussels must be depurated to eliminate any bacteria derived from sewage and other pollutants that may accumulate in the meat. This is accomplished by placing them in large tanks and circulating purified water through them for 48 hours. Large depuration plants have been constructed to mechanize the process.

Problems

Hydrographic conditions Salinity in Spain's Rio de Arosa is usually high, with a limited range of fluctuation. Once every six to seven years the river that feeds the bay floods and causes a freshwater lense to form on the surface. The top 1–1.5 meters of the culture lines may die.

Predators There is little predation by starfish and crabs. More dangerous are the sparid fish, which consume mussels by crushing them.

Fouling Organisms Ascidians and sponges grow on culture ropes and compete with the mussels for space and food. Barnacles and polychaete worms also tend to grow on the ropes.

Suitability of Raft Culture for Puget Sound

Raft culture of mussels in Puget Sound has a good prospect and is presently being used by growers in several locations, all of whom use or propose to use combinations of rafts and longlines. Rafts offer the utilization of three-dimensional space in the water, allow large quantities of mussels to be grown in a relatively small amount of space, do not restrict the operation to the beach area, (thereby allowing a wider selection of sites) and are inexpensive to construct. The quality of mussels produced on rafts is excellent: the meat is brilliant white and tender, and the flavor is mild and succulent. Penn Cove raft-grown mussels from Whidbey

Island have won two national mussel-tasting competitions.

Raft culture of mussels has met with some opposition from upland owners on Whidbey Island who do not like their view spoiled by the presence of rafts. Island County planners have concluded that longline systems are more suitable in view areas, because they are thought to be less of an eyesore than rafts.

Raft Culture in Puget Sound

Penn Cove Mussels, Inc. on Whidbey Island was the first mussel aquaculture venture started on the West Coast in 1974. Penn Cove is still the hub of mussel farming activity in Puget Sound: four out of seven Puget Sound mussel farms are located in Penn Cove. Log rafts were used to begin the first venture at Penn Cove Mussels, but they later replaced them with steel float rafts (Figure 7), and they now use a combination of rafts and longlines.

Catching seed in Penn Cove is not a problem. Each year ample seed is obtained by hanging lines from the rafts and catching natural settlements of mussel larvae. At times the settlement of mussels is even too dense and lines have to be thinned for unobstructed growout. Growth of mussels to harvest size in Penn Cove is rapid, from nine to ten months from larval settlement (market size is 50 millimeters). Most harvesting takes place in the spring and summer. The product is iced and delivered to wholesalers and to restaurants in Seattle and the Pacific Northwest.

One of the most severe problems faced by Puget Sound mussel farmers is predation on crops by scoter ducks. This is discussed in detail in Chapter 4.

Longlines

The most recent development in mussel aquaculture has been the use of longline systems for suspending culture ropes. Longlines are being used in countries that are just beginning to develop mussel culture. Similar to the Spanish raft culture technique, longlines employ ropes suspended underwater, not only for growth, but for catching seed as well.

Successful harvesting and experimental, pilot-scale, longline systems are being used and developed in many parts of the world. China has recently entered into mussel culture, and as of 1975 produced 100,000 metric tons of mussels with longlines and rafts. Sweden initiated large pilot-scale commercial operations in the shallow fjord basins on the northwest coast (Lutz, 1980). Longlines are used at Abandoned Farms on the U.S. east coast and in Puget Sound.

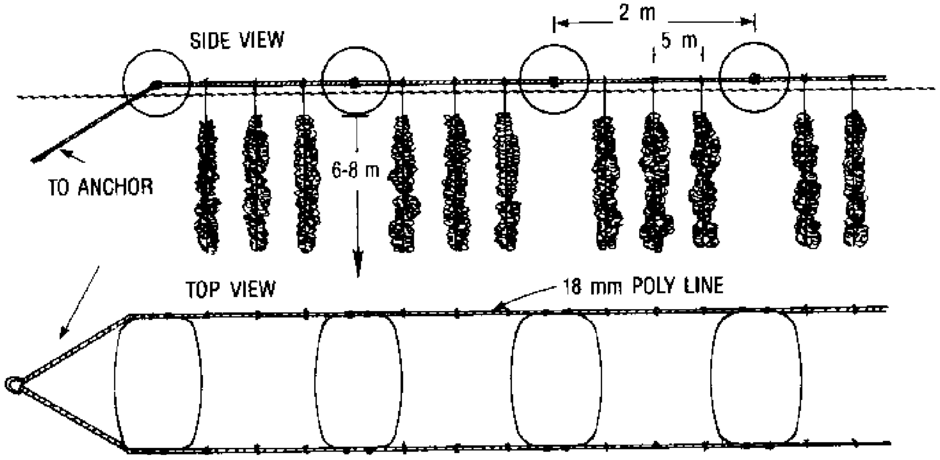


Figure 8. Longline systems of New Zealand.

New Zealand has also started an industry in mussel cultivation, utilizing longline systems (Figure 8) to grow the green-lipped mussel *Perna canaliculus* (Jenkins, 1979). During the 1970s, spatfall prediction studies revealed areas that could supply the growing industry with its needed seed supply. From that point there was a rapid proliferation of mussel farms in the Marlborough Sound of New Zealand. As of 1980 New Zealand farmers produced 1,000–1,500 tons of mussels per year, and are increasing production as they seek foreign markets for their mussels. *Perna* has also been found to have pharmaceutical value. It is said to contain a substance that relieves the symptoms of arthritis, and is powdered, capsulized, and sold for $10 per 40 capsules (*Aquaculture Digest*, 1984).

Seed Collectors

In Sweden and Puget Sound seed mussels will settle directly on culture ropes. Bare synthetic ropes are placed out in early spring to catch the main settlement of larvae. Settlement on the ropes is sparse enough in Sweden that thinning is unnecessary before harvesting.

Seed collection in New Zealand has become more of a science. At times massive settlements of *Perna* larvae occur on the rocks in certain areas, but to establish a viable industry, a dependable seed source is required. Through intensive research, Jenkins (1979) identified seed producing areas and a means to predict when and where seed collectors should be set out. His prediction method monitored many areas and each site was checked once a week for spatfall on the collectors. Once the spatfall reached commercial levels fishermen were advised to put out their seed-catching lines. New Zealanders use coir twine in bundles, fibrillated polypropylene wound on frames, and synthetic lines interlaced with fibrillated polypropylene for catching seed.

Grow Out

The longline systems used in New Zealand are similar to that used in China, Sweden, and the United States. Floats are made of polyethylene or fiberglass. Usable floatation displacement in New Zealand has been established at two-thirds of their total displacement, which is 450–650 pounds, 224–308 kilograms (Jenkins, 1979). The distance between floats varies. Figure 8 shows two-meter spacing between floats and ropes spaced every half meter. In New Zealand, seed mussels are sometimes kept in nursery areas before being placed on the final longline system. They are kept on special mini-longlines that can be surrounded by netting to protect the lines from predation by fish.

Cultured mussels grow rapidly once they are placed on growout lines. Seeding densities of 250 mussels/meter on a 16-millimeter diameter rope produce *Perna* of approximately 70 millimeters in 12 months, and 100 millimeters in 18 months. If the density is higher (approximately 750 mussels/meter) the growth would be 55 millimeters and 85 millimeters for 12 and 18 months, respectively. It is speculated that Marlborough Sound could produce 50 wet weight metric tons per hectare (2.47 acres) per year (Jenkins, 1979).

Problems

Predation Fish seem to be the main problem in the New Zealand mussel industry. Two species of fish endemic to the area, snapper and spotty, are known to feed on mussels. In shallower waters losses of up to 100 percent due to fish predation have been experienced. Predation by diving ducks—especially scoters—is a major problem in the Pacific Northwest. Longline systems generally cover a larger area than rafts, which allow more room for scoters to work, and are harder to protect against duck predation.

Fouling Organisms Organisms that settle on the culture ropes before and after seed settlement can cause problems. In New Zealand, ascidians, barnacles, and hydroids can colonize a rope and reduce its catchability before seed settlement has occurred. The most common cause for this dilemma is placement of the seed ropes in the water too early.

Weather Wind waves and strong currents can cause appreciable damage to longline systems and substantial loss of the mussel crop. Though longlines have a reputation of being able to withstand more adverse weather conditions than rafts, they are not completely weather resistant.

Suitability of Longline Culture

Longline systems for culturing mussels have a good outlook for use in Puget Sound. As mentioned, Whidbey Island county planners view the use of longline systems more favorably than rafts because they have less of a visual impact on upland owners' views than rafts.

Longline systems have been shown to better withstand the rigors of waves and currents than rafts. Secure anchoring of longlines is important, but once accomplished they can last through fairly harsh conditions. In New Zealand, longlines have been found to be low in capital cost, simple in design, biosuitable for keeping low density/unit area, aesthetically acceptable,and safe with regard to small pleasure boats (Jenkins, 1979).

2 SEED COLLECTION IN PUGET SOUND

Methods

A basic requirement of all mussel culture operations is secure supply of seed mussels. Although culture systems and methods of catching seed vary, mussel culture operations around the world have traditionally been located in areas where natural seed mussels are readily available every year (Mason, 1976).

Utilizing Natural Seed Beds

Many growers throughout the world utilize seed mussels that are available on rocks, pilings, or docks. Mussels are generally collected at a size of 1–2 centimeters and are handled in a variety of ways. A common method is to place the mussels in net socks (tubes). When full, these tubes are suspended from rafts or longlines and left to grow. The mussels, being semi-mobile at this stage, can work their way through the large mesh and continue growing while still attached to the mesh tubing. The result is a nice tubular shaped column of mussels.

Several types of net tubing are available, including the following:

1. Vexar
   Consolidated Net and Twine Co., Inc.
   1549 NW 49th
   Seattle, WA 98107
   Telex 7845100
2. Tenax
   RDB Plastotecnica
   22060 Vigano Brianza
   Via Del Industria 3
   Como, Italy
   Telex 335301
3. Norwegian Mussel Tubing
   Box 1135
   5001 Bergen, Norway
   Telex 42616
4. Nor Plex
   Northwest Plastic Extrusion
   P.O. Box 6172
   7800 S. 192nd Street
   Kent, WA 98023
   (206) 251-6050

Catching Seed on Collector Lines

An additional method of catching seed is to place collectors in the water for larvae to settle on. Rope, twine, or other materials are suspended in the water before peak settlement times; when larvae is abundant, a uniform set of mussels occurs. Many substrates have proved efficient in catching mussel larvae in Puget Sound. This study used rubberized curled-packing hair (RCH) as the standard for measuring larval settlement in different areas. However, when suspended in high settlement areas, not only did the RCH pads receive settlement, so did the PVC pipe frames to which they were attached, the rope on which they were suspended, and the netting that supported the RCH pads. It seems that mussels will settle on anything left in the water long enough.

The key factor involved in catching seed is the surface texture of the substrate. Mussel larvae prefer to settle on filamentous substrates, such as rope (hemp or coir) that has a bristly texture, or a PVC pipe that has diatoms and/or hydroids growing on it, giving it a filamentous texture. Data provided by Johnson (1980) suggest that hydroid and diatom growth on collecting substrates dramatically improve their larval collecting capabilities. Since in most areas of Puget Sound hydroids or diatoms will grow on submerged substrates in a matter of weeks, many methods can be used to obtain seed.

It is only necessary to submerge collectors for one month or a few weeks to obtain the proper settlement of hydroids or diatoms. Thus, the most important criteria are placement where sufficient settlement is expected and that the rope is fibrous, or has enough time to acquire the proper texture to attract mussel larvae.

It is apparent that the most cost-effective method of obtaining seed is to catch it on lines rather than scrape it from rocks or pilings. To catch seed, it is necessary to know when the peak settlement of mussels occurs and where the most likely settlement areas are. Realizing this need, two studies conducted by the University of Washington were modeled to determine when peak settlements occur for different areas in Puget Sound and what areas offer the best or most consistent settlement of mussel larvae. The results of these studies are described in the following section.

Mussel Larval Settlement in Puget Sound

Two separate studies to determine when and where mussel larvae settlement occurs monitored 17 sites and included most areas that could feasibly support a mussel culture facility. The study sites were chosen to represent a wide array of marine environments found in Puget Sound.

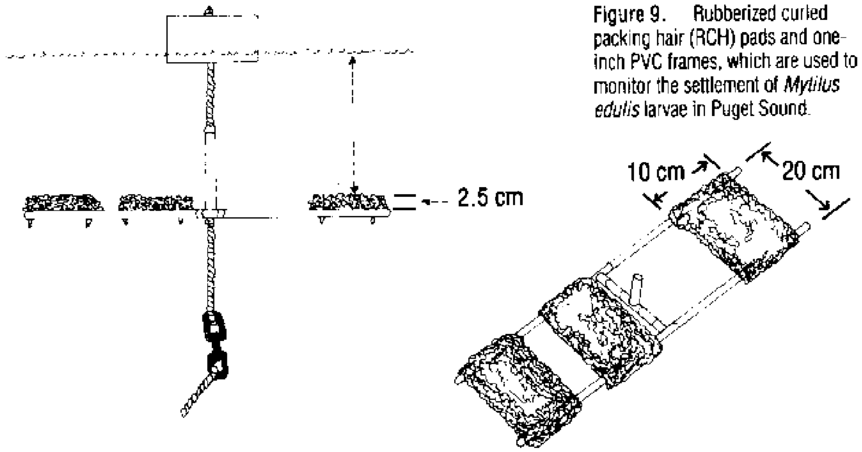


Figure 9. Rubberized curled packing hair (RCH) pads and one-inch PVC frames, which are used to monitor the settlement of *Mytilus edulis* larvae in Puget Sound.

Larval recruitment of *Mytilus edulis* was monitored by counting the number of plantigrades (newly settled mussel larvae) attached to collector substrates. Collector substrates made from strips of RCH material cut into pads and attached to frames of PVC pipe (Figure 9) were suspended by floats or docks so that they were continuously submerged. Samples were taken monthly or bimonthly and collectors replaced with a new RCH pad.

Counting Samples

Settled larvae of *Mytilus edulis* were removed from the collectors by emersing them in household bleach for eight minutes. Bleach oxidizes the mussel's byssal fiber attachments, thereby freeing them from the collector. Simply rinsing the collectors over stacked sieves, one-millimeter (#18) and 0.150-millimeter (#100) mesh size would retain newly settled mussels. Counting of plantigrades was done under a microscope in petri dishes. When samples contained more than 1,000 plantigrades per RCH pad, subsamples were taken to estimate their total number.

Areas Sampled

The 17 sites studied by Johnson (1980) and Skidmore (1983) were the following (Figure 10 a and b):

1. Budd Inlet, Department of Natural Resources marine station floating dock
2. Budd Inlet, West Bay Marina
3. Case Inlet, north side of Herron Island
4. Case Inlet, one mile north of ferry landing
5. Dabob Bay, Point Whitney shellfish laboratory dock
6. Dabob Bay, Camp Parsons dock
7. Eld Inlet, near The Evergreen State College
8. Fox Island, Washington State Department of Fisheries salmon net pens
9. Graysmarsh, wildlife refuge, Strait of Juan de Fuca, Sequim Bay
10. Holmes Harbor, dock near golf course
11. Manchester, National Marine Fisheries Service laboratory dock, east side
12. Manchester, NMFS laboratory dock, west side
13. Penn Cove, Coupeville dock, gas float
14. Penn Cove, Penn Cove Mussels, Inc. raft
15. Penn Cove, San de Fuca dock
16. Port Townsend, Union wharf
17. Squaxin Island, Squaxin salmon net pens in Peale Passage

Seasonal Patterns of Settlement

The majority of settlement occurred from late April through early July for the two years studied. Figures 11–15 show the seasonal fluctuations of *Mytilus edulis* larval settlement for the study sites. Most sites displayed the characteristic rapid increase to peak settlement level, then a gradual decrease within two to six months. By winter the majority of the study sites had virtually no mussel larval settlement activity.

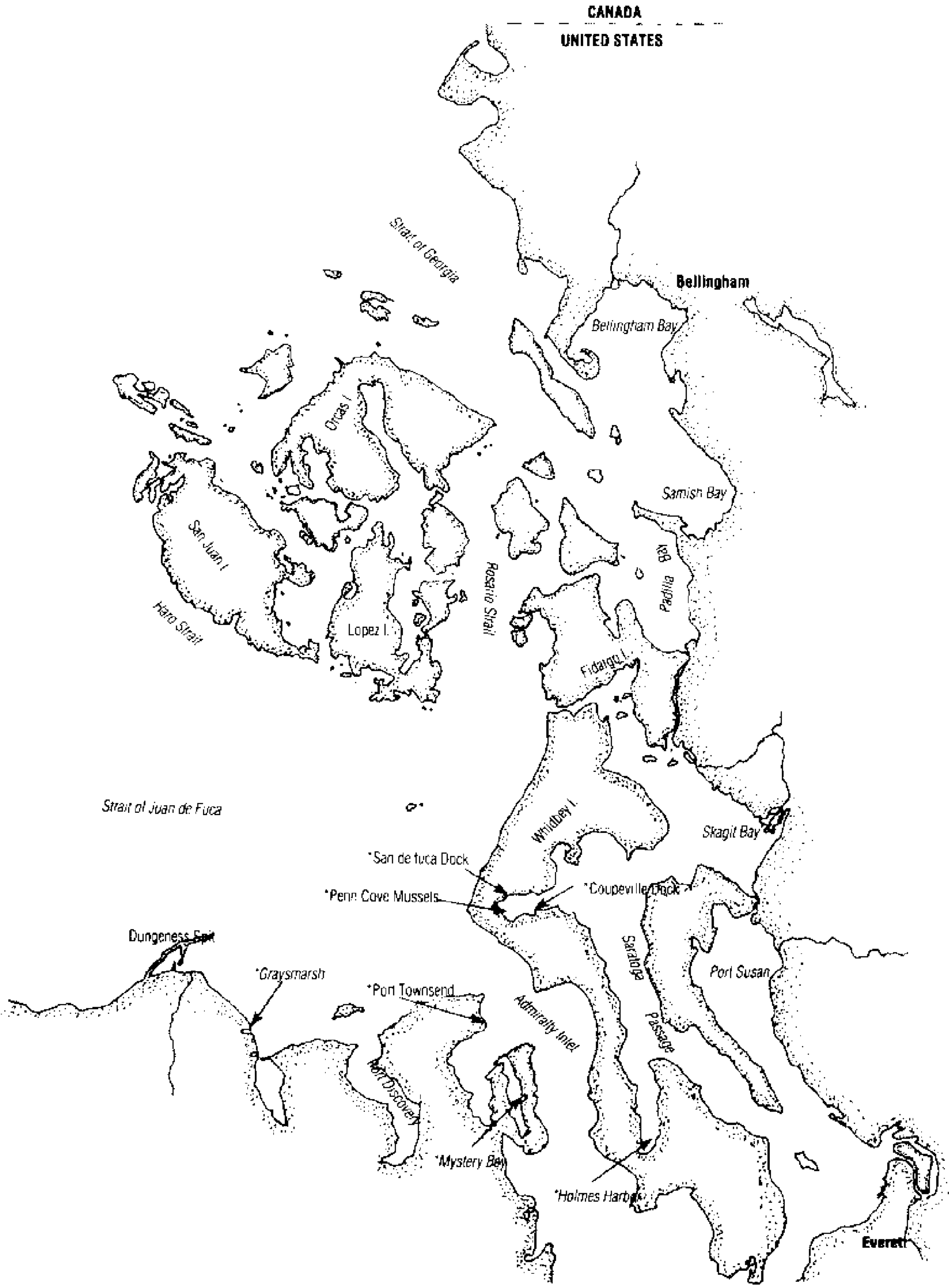


Figure 10A. North Puget Sound and the San Juan Archipelago. * indicates study site.

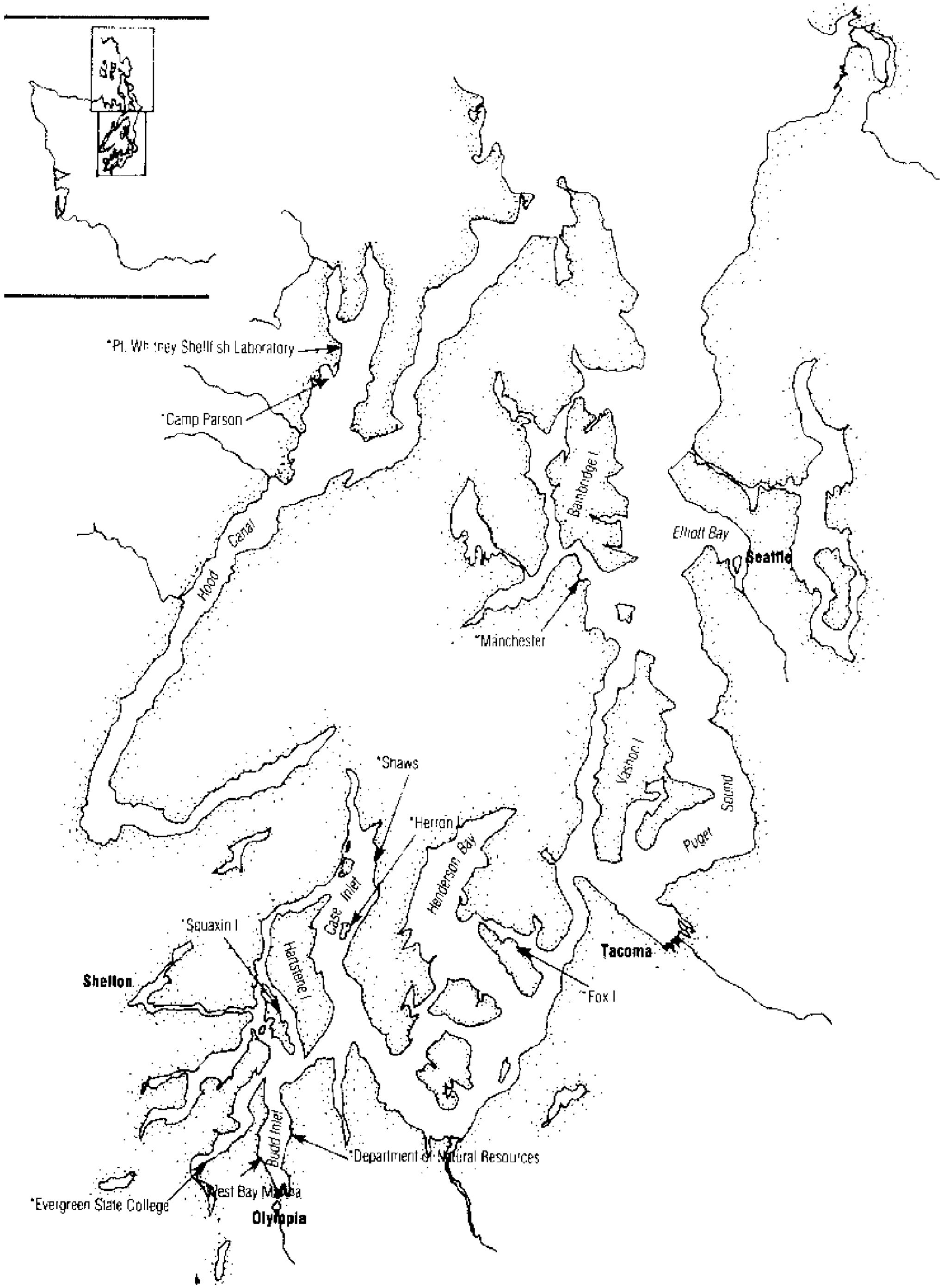


Figure 10B. Puget Sound and Hood Canal. * indicates study site.

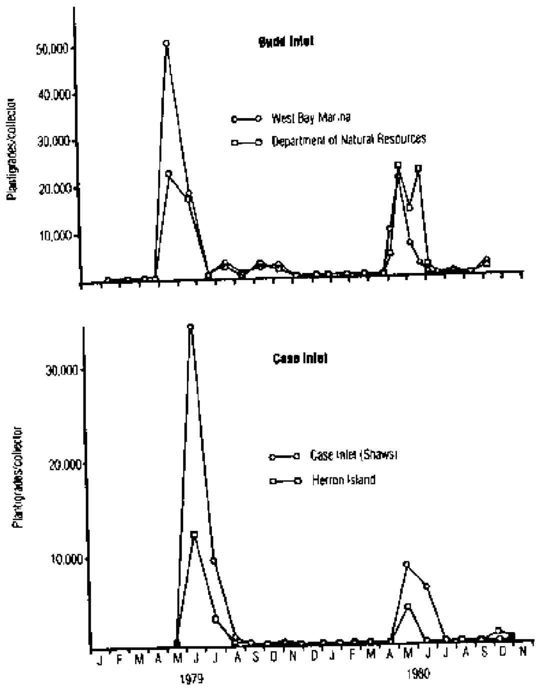


Figure 11. Numbers of *Mytilus edulis* larvae settled at Budd Inlet and Case Inlet.

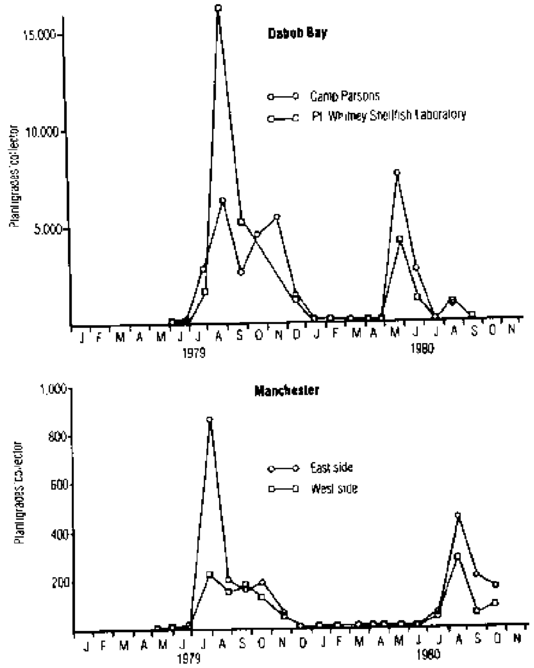


Figure 12. Numbers of *Mytilus edulis* larvae settled at Dabob Bay and Manchester.

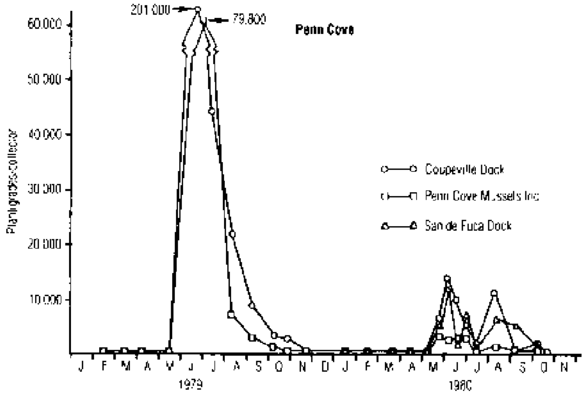


Figure 13. Numbers of *Mytilus edulis* larvae settled at three sites in Penn Cove, Whidbey Island, Washington.

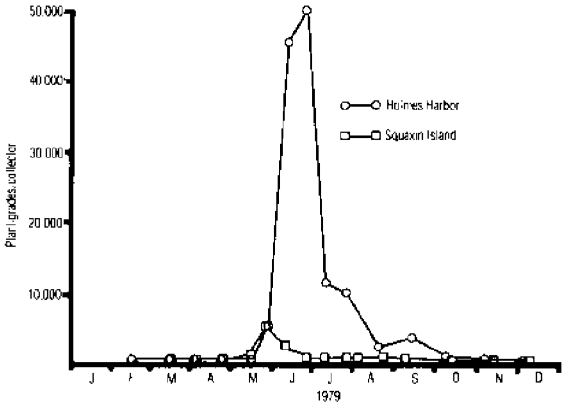


Figure 14. Number of *Mytilus edulis* larvae settled in Holmes Harbor, Whidbey Island and on the east side of Squaxin Island during 1979.

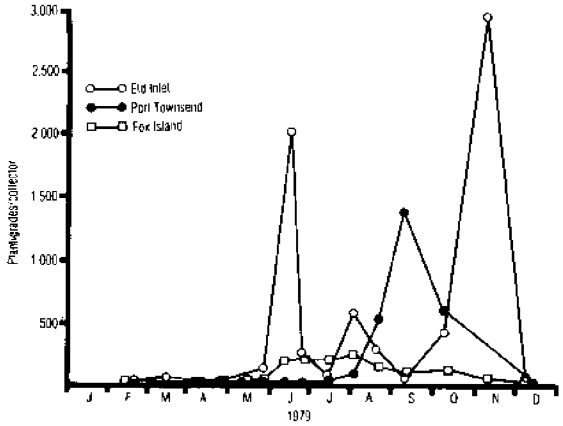


Figure 15. Numbers of *Mytilus edulis* settled at Eld Inlet, Port Townsend, and Fox Island during 1979.

Table 2 shows the largest numbers of mussel larvae collected for 1979 and 1980 and approximate settlement times. Most sites had peak settlements of larvae during late spring or early summer. Some sites had not one, but two settlement peaks, with one occurring in late spring and another in late summer or fall.

Settlement Densities

Numbers of plantigrades per RCH pad varied from area to area. Peak settlements ranged from 472,500 plantigrades on an RCH pad in Penn Cove to 232 per pad in Manchester (east). The ranking of peak settlements from all sites reveal large variations in settlement in Puget Sound (see Table 3).

In 1979 Penn Cove had the highest levels of mussel larval settlement of all areas studied. Counts of plantigrades were 472,500, 201,500 and 79,900 plantigrades per collector pad for the three areas studied in Penn Cove. These were found to be adequate, if not too dense, for use by mussel growers in that area.

In 1979 and 1980 (Table 2) there was a large difference in settlement on Penn Cove Mussels Inc. rafts, although owner Peter Jefferds expressed satisfaction with the sets. In fact, in both cases the settlement required thinning because they were too dense for uninhibited growout. Four thousand plantigrades per RCH pad could be considered a viable commercial settlement. However, areas with higher settlement levels are more likely to receive a consistent settlement than those on the lower end of the scale.

Why Some Areas are Better than Others

Because of the wide range of physical properties contained in the areas studied, some generalizations can be made as to what makes up a good site for catching mussel larvae. Settlement was greater in protected bays and inlets, where the newly spawned larvae were less likely to be swept away by tides, currents, or wind-created mixing.

Penn Cove had the highest larval settlement rate of all areas studied. It is a protected and fairly stable body of water, has a slow flushing rate, and during spring and summer there is little wind-created mixing. Nearby, the Skagit River introduces nutrient-rich water that slowly enters the Penn Cove system. Enormous diatom and dinoflagellate blooms continue nearly all spring and summer. These blooms feed a large natural mussel population and supply large swarms of larvae with adequate food. A great proportion of larvae are able to survive and remain in the cove long enough to settle.

Manchester, by contrast, had the lowest settlement rate of the study areas. Its waters are almost always well mixed, stratifying only on neap tides during long warm days in summer. It is part of Rich's Passage, which is a flushing channel for Port Orchard and Sinclair Inlet. Thus, any larvae spawned at Manchester are likely to be swept away or mixed into the water to produce only sparse concentrations. The timing of settlement is also affected by physical properties of the water.

Johnson (1980) found that there was a gradient in timing of settlement from the extreme inlets of southern Puget Sound and the Saratoga Basin to the Strait of Juan de Fuca. In his study the earliest settlement occurred in the spring in south Puget Sound and Saratoga Basin. Settlement was increasinly later at Fox Island, Manchester, Port Townsend, and Graysmarsh. Essentially, the more influence from the main basin waters, the later the mussel settlement. Settlement peaked in summer in the main basin of Puget Sound and Strait of Juan de

Table 2. Peak settlements of *Mytilus edulis* larvae and settlement period for various areas of Puget Sound

	1979		**1980**	
Location	**Plantigrades per collector**	**Settlement period**	**Plantigrades per collector**	**Settlement period**
Budd Inlet				
A) Dept. Nat. Resources	22,500	May-June 21	23,200	May 8-22
B) West Bay Marina	50,300	May-June 21	21,640	May 8-22
Case Inlet				
A) Herron Island	12,400	late May-June 15	4,260	late April-May 15
B) Shaws	34,500	late May-June 15	8,930	late April-May 15
Dabob Bay				
A) Pt. Whitney	6,360	August-November	7,520	late April-May 23
B) Camp Parsons	16,300	August-September	4,124	late April-May 23
Manchester				
A) East	236	late July	227	late July-August
B) West	862	late July	453	late July-August
Penn Cove				
A) Coupeville dock	201,500	late May-June 15	13,800	late May-June late July-August
B) Penn Cove Mussels, Inc.	79,900	late May-June 15	3,876	May-June
C) San de Fuca dock	—		11,900	May-June August-September
Holmes Harbor	57,800	late May-June		
Squaxin Island	6,900	May-June		
Eld Inlet	3,200	late May October-November		
Port Townsend	1,600	July-mid September		
Fox Island	336	late Spring-early summer		
Graysmarsh	264	late August-November		

Table 3. Ranking of sites by numbers of plantigrades at "peak settlement" for 1979. Indicated numbers are an average of 2 or 3 RCH pads.

Sample Site	**Plantigrades/RCH pad**	
	1979	**1980**
Penn Cove, Juan de Fuca dock	472,500	11,900
Penn Cove, Coupeville dock	201,500	13,800
Penn Cove, Penn Cove Mussels Inc. raft	79,900	3,876
Holmes Harbor, Golf course dock	57,800	
Budd Inlet, West Bay Marina	50,300	21,640
Case Inlet, North of Ferry landing (one mile)	34,500	8,930
Budd Inlet, Department of Natural Resources dock	22,500	23,200
Dabob Bay, Camp Parsons	16,300	4,174
Case Inlet, Herron Island	12,400	4,260
Squaxin Island, Salmon net pens	6,900	
Dabob Pay, Whitney Pt. Shellfish laboratory	6,400	7,520
Eld Inlet, near Evergreen State College	3,200	
Port Townsend, Union Wharf	1,600	
Manchester, West	862	453
Fox Island, Washington Dept. of Fisheries net pens	336	
Graysmarsh, Wildlife Refuge	264	
Manchester, East	232	273

Fuca. Lower water temperature closer to the Strait of Juan de Fuca may have partially explained the delayed settlement times.

Larval Settlement Prediction Model

Johnson (1979) found that it was possible to predict the time of mussel larval settlement by either correlating degree-days that the larvae were present in the water or by counting the number of eyed larvae in the water.

Temperature Model

It was suggested in the literature and found by sampling in Puget Sound that the length of time larvae are free-swimming before settling is affected by the temperatures they encounter. Warmer water generally hastens the development of the larvae, (concluded by Bayne, 1965) up to 14°C. However, if the water is warmer than 14°C no significant increase in development occurs. Johnson calculated a value of 496 day-degrees for full development and settlement for mussel larvae in Puget Sound. This value is calculated by adding the daily temperature of the water from the time of mussel spawning to the time of larval settlement. Larvae in Holmes Harbor settled after five to six weeks.

Correlation of Eyed Larvae to Settled Larvae

Johnson also found the number of eyed larvae occurring in the plankton was a good indicator of when settlement would occur: in Holmes Harbor, for example, an increase in eyed larvae was rapidly followed by a sharp increase in larvae settling. The number of eyed-larvae in the plankton increases sharply before settlement. The term "eyed" larvae refers to a conspicuous dark spot that appears inside the shell of the free-swimming larvae before they begin searching for a site to settle. This spot is thought to have some use as far as orientation to light. Settlement times can be estimated closely using water temperature and eyed larvae counts.

Hatchery Rearing of *Mytilus edulis* Larvae

At the onset of the mussel culture studies at the University of Washington, catching wild seed was a major obstacle with the two sites selected. Researchers therefore decided that to obtain consistent supplies of seed it would be necessary to produce it in a shellfish hatchery. Waterstrat (1979) experimented with rearing *Mytilus edulis* larvae to setting size at the National Marine Fisheries Services laboratory experimental hatchery in Manchester.

Mytilus edulis were difficult to spawn. To induce spawning the mussels were placed in elevated seawater, 18–23°C, for up to two hours. If this did not induce spawning they were treated with chemical stimulants, KCl (2 grams per liter), H202 (Morse et al., 1977), and sperm suspensions obtained by stripping male mussels. Normal fecundity was from 300,000 to 6 million eggs per individual.

Once eggs were collected they were fertilized with a small amount of sperm, and held in 150-liter circular tanks in a static water system at 15–21°C. Densities of larvae in the tanks were less than five per milliliter at the straight hinge size.

Survival rates of larvae from egg to straight hinge stage was 13.5 percent; from straight hinge to settlement size survival was 3.3 percent. Several batches were lost to bacterial infections of *Vibrio anguillarum*. In all, 914,000 setting-sized larvae were produced from 206 million fertilized eggs. The maximum recorded survival from egg to metamorphosis stage was 1.14 percent for all experiments.

Settlement

Three substrates were tested in the tanks for their ability to catch settling mussel larvae. They were Synclove rope, RCH material, and fiberglass filter material, all of which had a filamentous texture required for settlement. Although the preferred settlement substrates were filamentous, a large proportion of larvae (20–74 percent) settled on the sides of the tanks, which offered the largest surface area for settlement.

3 GROWTH, MORTALITY, AND CONDITION OF *Mytilus edulis* AND *Mytilus californianus* IN PUGET SOUND

In Puget Sound, growth rates of mussels have been found to be comparable to those of the best growing regions in the world. Harvestable crops—*Mytilus edulis* is considered harvest size at 50 millimeters (2 1/2 inches)—have been produced in less than one year by Penn Cove Mussels on Whidbey Island. During 1983, the year of the influence of *El Niño*, mussels caught on seed lines in May were harvestable in December and January. Though this was somewhat unusual due to the warm weather during that winter, mussel growth during a normal year is only slightly slower. In some areas of Puget Sound *Mytilus edulis* grew well but suffered mass mortalities during summer months. This prompted the evaluation of another mussel species, *Mytilus californianus*, as an aquaculture candidate in these areas.

In the studies to be presented, mussels were grown in several areas of Puget Sound to determine suitable aquaculture sites. Sites were chosen based on tests covering a broad scope of marine environments within Puget Sound, from productive distal inlets to less productive tidal channels. Results presented will include studies following growth and mortality of mussels grown at five different areas in Puget Sound, evaluation of the growth of seed mussels gathered from three different areas in Puget Sound, condition index or fatness of *Mytilus edulis*, growth and survival comparisons of *Mytilus californianus* with *Mytilus edulis*, evaluation of *Mytilus californianus* culture potential, and hatchery experiments with *Mytilus californianus*.

Growth and Mortality of *Mytilus edulis*

Seasonal changes in growth and mortality rates were recorded for five areas in Puget Sound (Table 4). In addition, water samples were analyzed to determine the quantities of food available in the water to filter feeders. Results presented here are from Skidmore (1983).

Specimens of *Mytilus edulis* were collected from the undersides of floating docks at the Department of Natural Resources in Budd Inlet near Olympia, Washington. Average size of the seed mussels collected was 7.63 millimeters ± 0.51 millimeters and were estimated to have settled two months prior to their transfer to growout areas.

One hundred seed mussels were placed in experimental flow-through cages suspended one meter below the surface (Figure 16). Cages were constructed from five-gallon plastic buckets with side panels replaced with vexar plastic grid material. Protection of the seed mussels was necessary to avoid predation by diving ducks, pile perch, and crabs.

The mussels were removed from the cages on a monthly basis and separated, individual shells were measured, and mortalities were recorded. Dead or missing mussels were replaced to maintain the density in the cage at 100. Any accumulation of fouling organisms on the cages were removed at each sampling.

Suspended particulate material was sampled from seawater at Case Inlet, Manches-

Table 4. Experimental grow-out sites of *Mytilus edulis*.

Area	**Site**
Budd Inlet	Department of Natural Resources dock, Olympia
Case Inlet	A float 200 m offshore, one mile north of the Herron Island ferry landing
Dabob Bay	Washington State Shellfish Laboratory dock, Pt. Whitney
Manchester	National Marine Fisheries Service, Marine Lab dock
Penn Cove (See map; Figure 10)	Penn Cove Mussels Inc., raft

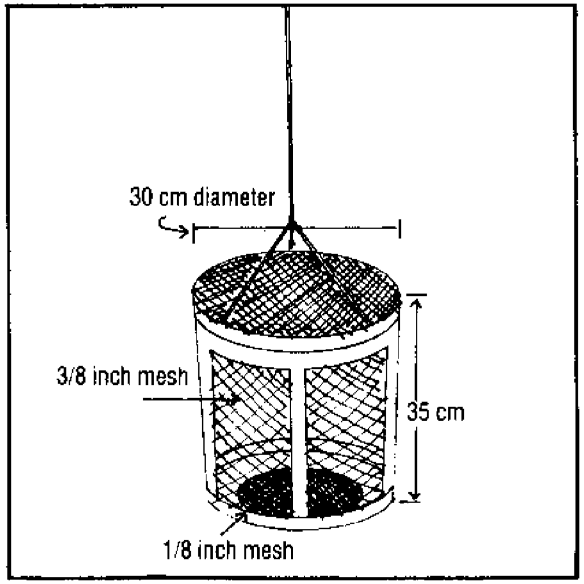


Figure 16. Flow through growth cage used to hold *Mytilus edulis* in a growth experiment at five areas in Puget Sound. Each cage holds 100 mussels.

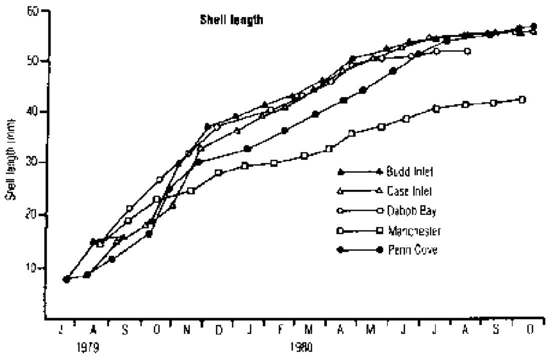


Figure 17. Average shell lengths of *Mytilus edulis* grown at five areas in Puget Sound.

ter, and Penn Cove, and analyzed using methods described by Strickland and Parsons (1972) to determine the weight of microscopic materials present. Particles used by *Mytilus edulis* as food are 5–250 micrometers in size. Only particles within this size range were used in food comparisons. Study areas were compared, estimating the food available by the dry weights of retained particles. Total particulates (dry weights) and particulate organic material (ashed weight) were determined (Bayne and Widdows, 1978).

Growth Results

Mytilus edulis, grown at four of the five experimental sites in Puget Sound, attained market-sized shell length (50 millimeter) within 12 to 13 months. Mussels grown at Manchester were the only group not to attain the average size of 50 millimeters even though they were grown for 18 months. Growth rates of *Mytilus edulis* for the five areas are shown in Figure 17. Since seed mussels for all five sites were collected from the same area (Budd Inlet) and grown in identical cages, differences in growth rates were attributed to their growing environment.

Rapid growth rates occurred during the first summer and fall with the most pronounced growth between the sizes of 15 and 35 millimeters. In some areas the most rapid growth was during October and November. When observing increments of growth per month it was possible to categorize the growing areas into two distinct groups (Figures 18a and b). Slower growth areas (Figure 18a) were found to have a decreasing growth rate through the experiment, while the higher growth areas (Figure 18b) had "growth bursts" during October and November. Growth increments per month reached 12.6 millimeters per month during the fall months in high growth areas, while a maximum of six millimeters per month was measured in the slower growth areas. One possible explanation for the different growth rates was the food found in those particular areas of Puget Sound.

Seawater Analysis

Particulate organic matter (POM), as a fraction of the seston in seawater, can be construed as a gross indicator of available food to filter feeding animals (Widdows, 1978). Case Inlet, Manchester, and Penn Cove showed that POM varies for different areas of Puget Sound (Figures 19 and 20). Penn Cove had the highest POM weight with 8.56 milligrams per liter during mid-August. Manchester had the lowest seasonal maximum of the three areas studied with 4 milligrams per liter. However, Manchester had the highest percentage POM of total seston, with 83 percent. Maximum weight of total seston was 10 milligrams per liter recorded in June in both Penn Cove and Case Inlet.

Factors Affecting Growth

Mytilus edulis, being a filter feeding animal, is dependent upon plankton, organic detritus, bacteria, and probably dissolved organic matter (DOM) in the water as sources of food. In aquaculture operations, population densities, growing depths, and predation can be controlled to optimize growth, but food supplies can only be reasonably controlled through site selection. Therefore, to assure fast growth, mussel aquaculturists must locate their operations in productive bays.

In this study the growth of mussels was compared to the amount of food in the water, represented by total seston and POM. Faster growth rates and larger ultimate size appeared to be related to the amount of food in the water. After sampling water over eight months from Penn Cove and Manchester for POM, it became apparent that there was more food available to mussels as POM and total seston in Penn Cove than at Manchester.

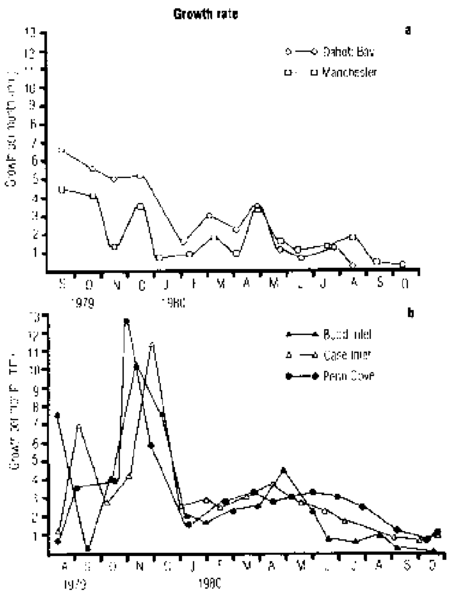


Figure 18. Average monthly growth increments in shell lengths of *Mytilus edulis* grown at five locations in Puget Sound: (a) is the slower growth areas, and (b), having "growth bursts" in fall are the faster growth areas.

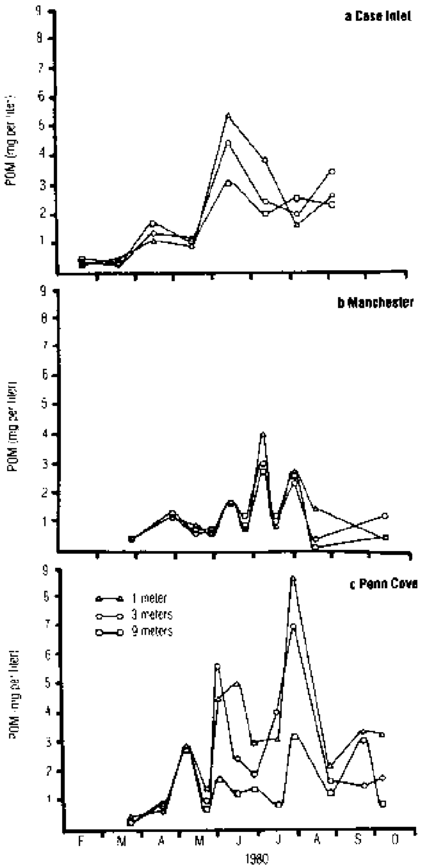


Figure 19. Right: Particulate organic matter (POM) from one liter samples taken from (a) Case Inlet, (b) Manchester, and (c) Penn Cove.

During most of the year Penn Cove waters are turbid, rich, and light-green in color. Temperature gradients and salinity differences can be detected in its surface layers. Dense layers of phytoplankton and suspended particulates can be seen while scuba-diving. These warm, nutrient-rich surface layers support large blooms of phytoplankton that feed the rapidly growing mussels. The clear, deep blue waters at Manchester, however, are well-mixed and exchanged daily with main basin waters of Puget Sound. Only rarely at Manchester will a thermocline or halocline develop. Suspended particulates and plankton are well mixed into the water column and rarely form dense aggregations. Thus, large blooms of phytoplankton to support fast growth are rarely available at Manchester.

Mortalities

At 18 months of age, the average cumulative mortality of mussels was approximately 80 percent (Figure 21) for all five areas tested. After six months of the experiment some mortalities were seen at Manchester. The other four areas had no significant mortalities until

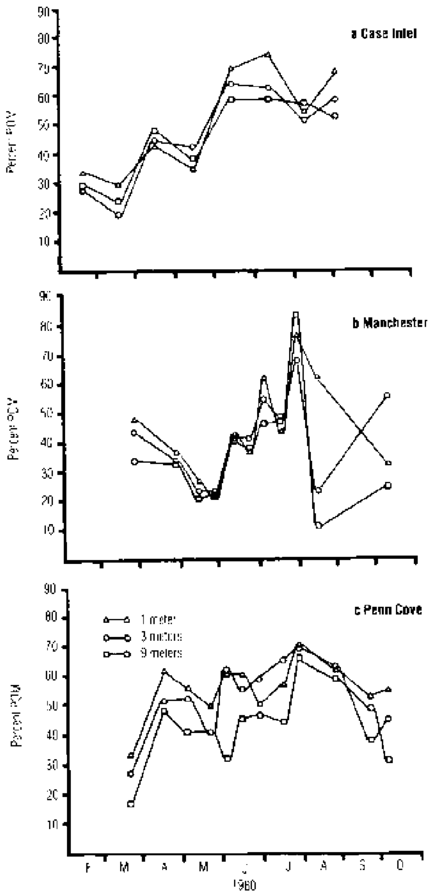


Figure 20. Percent Particulate Organic Matter (POM) of one-liter samples taken from a) Case Inlet, b) Manchester, and c) Penn Cove.

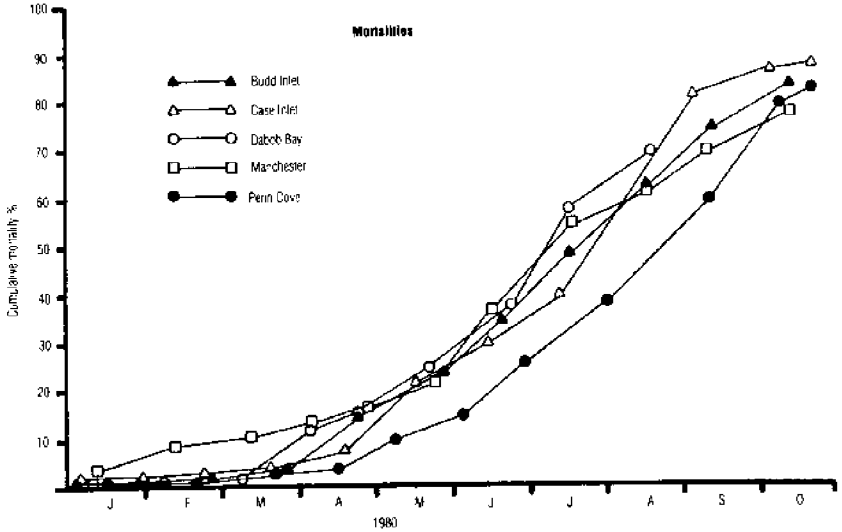


Figure 21. Cumulative mortalities of *Mytilus edulis* grown in growth cages at five locations in Puget Sound. Seed mussels were calculated to have settled during May 1979. No appreciable mortalities occurred until January 1980.

March or April. Most mortalities occurred during the spring and summer and continued until the experiment was terminated in October 1980.

Mortalities of this magnitude could obviously reduce, if not negate the profits realized in an aquaculture venture. At this writing no scientifically backed theory has been formulated to explain the mass-mussel mortalities, but the phenomenon is being studied (Taylor, personal communication). Investigators are trying to better understand mussels' reproductive strategies and physiological reactions to certain conditions.

Comparative Growth of *Mytilus edulis* from Three Seed Sources in Puget Sound

Mussels are found in almost every bay or inlet in Puget Sound, but they differ in growth rates, longevity, condition index cycles and shell morphology (Johnson and Chew, 1981; Johnson, 1982; Skidmore, 1983). Different areas display different environmental conditions and may be isolated from each other in that there is little or no exchange of gametes between areas. Areas such as Hood Canal, South Sound, or even smaller bays or inlets may be entirely genetically isolated and their gene pools may evolve independently from others. Mussels can adapt to local conditions and react to varying environmental conditions in different ways. To test the effects of genetic differentiation on isolated areas of Puget Sound (Figure 10), Washington State Department of Fisheries followed growth and survival rates of mussels in Penn Cove; Whitney Point in Dabob Bay; and Squaxin Island near Peale Passage in South Puget Sound (Johnson, 1982). Juvenile mussels (10 to 15 millimeters) were collected from

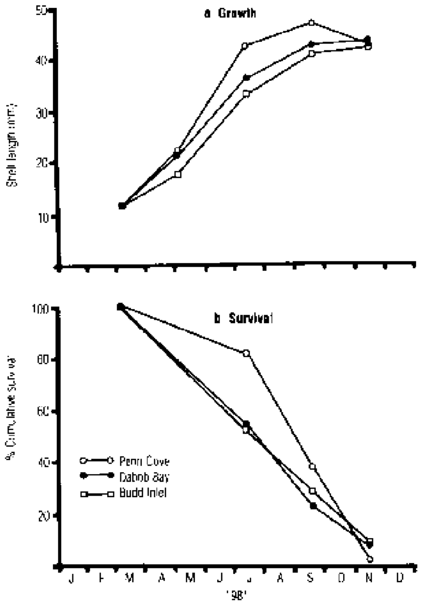


Figure 22. Growth and survival of mussels from three seed sources grown at Penn Cove.

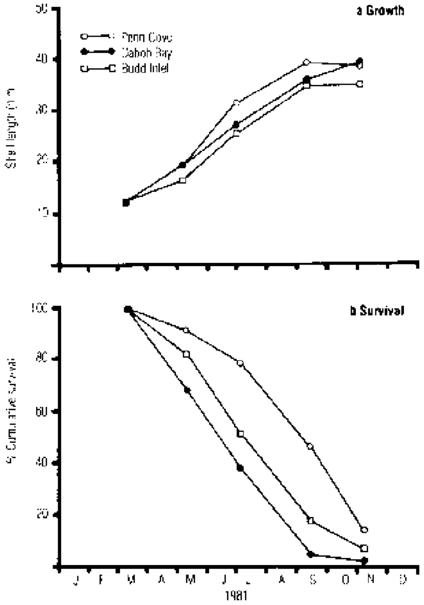


Figure 23. Growth and survival of mussels from three seed sources grown at Manchester.

each area and placed in cages covered with vexar 1/2-inch plastic netting to protect them against predation. Arrays of duplicate cages with mussels from the three seed sources were set up at each of the three test growth sites during February 1981.

Results

Penn Cove Penn Cove seed produced the largest mussels over nine months (Figure 22a). The growth curves are a typical sigmoidal shape inherent to the growth characteristics of many bivalves. Figure 22a shows a drop in the size of mussels from Penn Cove during September to November. This was due to starfish intruding into the cages and eating the larger mussels. However, until the starfish invasion, Penn Cove seed had exhibited faster growth than the other two populations.

Meat content of mussels was also compared (dry meat weights per mussel) for the three seed sources grown at Penn Cove. At Penn Cove dry weights of the three seed populations did not differ significantly at the end of the study.

Survival of mussels grown at Penn Cove was also affected by starfish predation (Figure 22b). Like growth rate, survival among Penn Cove mussels was superior until the predation indicating that Penn Cove mussels seemed to survive better, although survival for all seed sources was quite low.

Manchester Tests show that the shell lengths of the three stocks of mussels grown at Manchester differed significantly in September, with Penn Cove seed attaining the greatest length and Budd Inlet the least (Figure 23a). Survival was found to be low in all seed sources by the end of the experiment, but Penn Cove seed survived better (although still low) than Dabob Bay and Budd Inlet seed (Figure 23b). The seed sources also differed in dry weights of meat at the end of the experiments. Dabob Bay seed achieved greater dry weights than Penn Cove and Budd Inlet seed.

Squaxin Island At this site Penn Cove mussel seed again attained the largest shell lengths and had better survival than the other two seed sources tested (Figures 24a and b). Mussel dry weights differed between seed sources with Dabob Bay having the highest meat weight followed by Budd Inlet and Penn Cove.

In summary, the best growth rates were attained with Penn Cove and Budd Inlet seed grown at Penn Cove and Squaxin Island. Seed from Penn Cove provided the best growth in all three water areas tested. In evaluating the growth potential of the three locations, Manchester is the poorest, while Penn Cove and Squaxin were similar.

Differences in growth among the three seed populations in this experiment may be indicative of genetic differences. Electrophoretic techniques (chemically plating chromosomes) have revealed differences in allele frequences in mussels on the east coast of North America from the intertidal zone (Koehn et al., 1973) in estuaries (Koehn et al., 1976), and within the Canadian Maritimes (Gartner-Kepkay et al., 1980). Thus, it is very likely that differences in genetic make-up caused the variations seen in this study.

The possibility of finding a superior growing or surviving mussel for culture is an important factor for a mussel aquaculturist to consider. A superior seed source could benefit the emerging mussel aquaculture industry. Though transferring seed from one site to another is labor-intensive, the benefits from faster growth and better survivorship may far outweigh the additional labor costs.

Condition Index

Condition indices can be considered a measure of "marketability" or "fatness" of a bivalve, or more precisely, the tissue weight relative to shell parameter. At times, the meats of mussels are extremely small due to spawning or other considerations, which reduces their market acceptance. If detected, it may be prudent to restrict the harvest of mussels during this period. In Belgium and other large mussel-producing countries, harvest is suspended during and after spawning. In fact, mussels from wild subtidal beds on the east coast of the United States are not harvested during the summer months due to poor meat condition due to spawning.

In Puget Sound mussels follow distinct condition patterns related to water temperature and food regimes. Johnson (1980) and Waterstrat (1979) studied the condition index of Puget Sound mussels. Some generalizations from their work are made which are presented in the following section.

Condition Index Evaluations

Numerical values to express condition index can be obtained by using several methods. One standard method follows Westley (1959):

$$\frac{\text{Dry weight tissue (grams)}}{\text{Volume of shell cavity (ml)}} \times 100 = \text{Condition Index}$$

Using this method, an oyster is marketable when it has a condition index value of 10 or greater. A similar value is as yet undetermined for mussels in Puget Sound.

Condition index of mussels have, in the past, been based on several shell parameters:

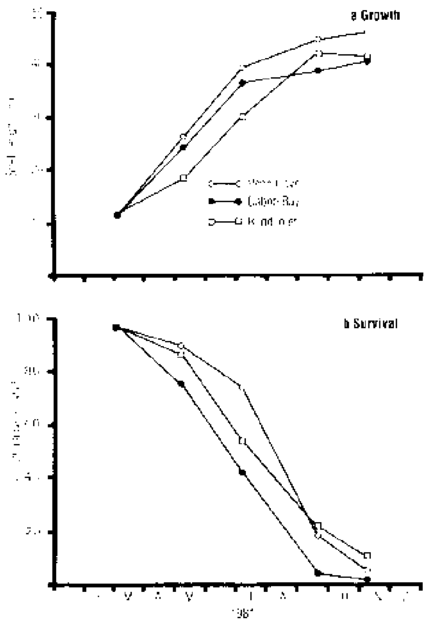


Figure 24. Growth and survival of mussels from three seed sources grown at Squaxin Island.

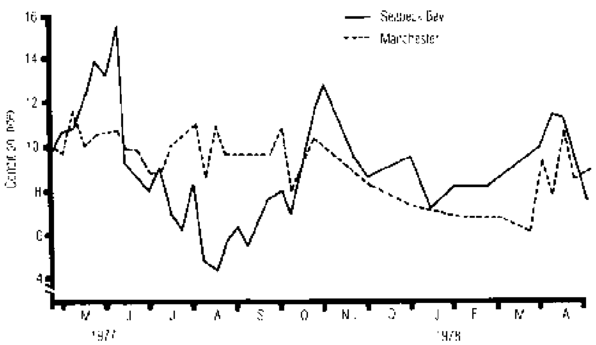


Figure 25. Condition index of adult, raft-suspended *Mytilus edulis* at Seabeck and Manchester. Calculated by (Dry tissue wt. (grams)/ vol. of shell cavity (ml)) x 100 C.I.

volume, weight, and length. All of these methods have some degree of error involved in their calculations. In the first experiment, Waterstrat used Westley's method for determining condition index of mussels grown at Seabeck and Manchester. For the second experiment, Johnson used the dry weight of tissue/shell weight × 100.

Seabeck and Manchester

Mussels in a culture situation were monitored from April 1977 to April 1978 for condition index. During that time Seabeck was characterized by rather large fluctuations of condition index over relatively short time periods (Figure 25). Manchester showed a more stable pattern of condition index. These patterns may be due to large changes in environmental conditions at Seabeck and the more stable conditions at Manchester. Food and temperatures appeared to fluctuate more widely at Seabeck than at Manchester.

Changes in condition index appeared to reflect the spawning cycle of *Mytilus edulis*. The condition index was seen to increase until mid-June at Seabeck, followed by a dramatic drop. This drop was the result of the mussels spawning. The highest abundance of mussel larvae in the water at Seabeck corresponded with the lowest levels in condition of adult mussels. The annual cycles of Seabeck mussels were similar to those of intertidal mussels reported by Seed (1975) and for rope cultured mussels by Mason (1976).

Dramatic changes in condition index did not appear at Manchester; however, a decline in condition index corresponding to a decline in temperature during late fall and winter was observed. Relatively stable temperatures, salinities, condition index, and larval abundance at Manchester suggested that spawning may be prolonged.

Eight Station Study in Puget Sound

In this experiment eight sites were monitored for the condition index in mussels. The sites were Fox Island, Budd Inlet, Eld Inlet, Manchester, Holmes Harbor, Penn Cove, Dabob Bay, and Mystery Bay (see map, Figure 10).

Differences in condition index existed between stations and between seasons. Some generalizations can be made about the events seen in 1979. Five stations (Budd Inlet, Fox Island, Manchester, Penn Cove and Dabob Bay) exhibited two periods of high conditions: spring through early summer, and mid-summer through fall. Periods of low condition were winter, late autumn, and a short period during summer. Complete results are found in Figure 26. The average condition index for each of seven areas shows the large differences found in Puget Sound (Table 5).

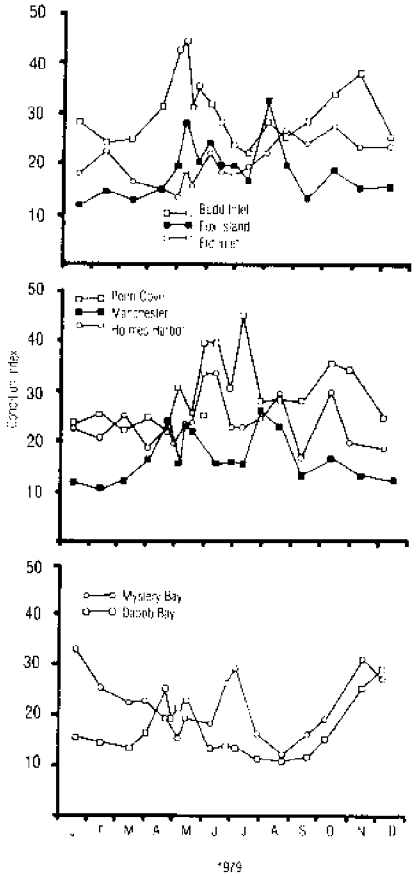


Figure 26. Condition index of mussels, *Mytilus edulis*, at eight locations in Puget Sound.

Dry Weight Comparisons

The best way to compare the condition of many stations is by dry weight of tissue, because it eliminates calculations of shell lengths, weight, or volume and allows direct comparison of intertidal and subtidal mussels. Normally, differences in shell volume and weight between similar sized intertidal and subtidal mussels preclude reasonable comparison. Table 6 shows mean dry tissue weights from mussels with similar shell lengths at the eight sample sites.

Factors that Influence Condition and Tissue Weight

The most important factor affecting condition of mussels is the available food and flow of water past the mussels. An average-sized mussel (50 millimeters) can filter about 1.5–2 liters of water per hour (Foster and Smith, 1976), but if there is not adequate flow of water past the mussels, available food in the immediate vicinity may be depleted.

Spawning dramatically affects condition during spring, but average mean values for

Table 5. Average condition index for *Mytilus edulis* calculated by (dry tissue wt/shell wt) × 100 = CI.

Station	Mean condition index
Budd Inlet	31.3
Penn Cove	29.0
Holmes Harbor	23.3
Mystery Bay	21.3
Fox Island	19.5
Dabob Bay	17.4
Manchester	16.8

Table 6. Dry tissue weights for 1979 of mussels at eight sites in Puget Sound. Mussels from all sites were collected from floats except at Eld Inlet.

Station	Mean dry tissue weight
Budd Inlet	3.56
Eld Inlet (intertidal site)	3.37
Penn Cove	3.36
Mystery Bay	2.68
Holmes Harbor	2.61
Fox Island	2.53
Manchester	2.10
Dabob Bay	1.65

the year are most affected by food availability. Freeman (1974) noted a spring and fall condition maxima related to phytoplankton blooms, which persist longer and occur from March through September in south Puget Sound. Food for filter feeders is abundant most of the year.

Food availability for mussels in the main basin of Puget Sound is less than in the south Sound. Although phytoplankton production is high during blooms, they come and go rapidly. Continual feeding in some areas instead of burst feeding may account for differences in condition.

Growth and Survival Comparisons of *Mytilus californianus* and *Mytilus edulis*

The California mussel (*Mytilus californianus*) is found on rocky shores from Mexico to the Aleutian Islands on the Pacific Coast (Soot and Ryan, 1955). The intertidal zone of coastal, rocky shores washed with waves and scoured by storms are a likely place to find *Mytilus californianus* thriving. California mussels grow much larger than bay mussels. They attain sizes of up to 25 centimeters (10 inches) in shell length. They can be distinguished from bay mussels by the presence of radiating ribs on the shell originating from the umbo area.

California mussels grow along the entire outer coastline of Washington state where there is suitable substrate. They are also found in the Strait of Juan de Fuca, but their populations diminish in size and diversity approaching Admiralty Inlet and no large populations exist in Puget Sound.

After several years of research it became apparent that *Mytilus edulis* could feasibly be cultured in Puget Sound. Prospects for a successful industry being started in Puget Sound were good. However, some areas that appeared perfectly suited for the culture of bay mussels and offered a protected site for raft or longline culture were found to induce mass mortalities.

Areas south of the Tacoma Narrows were characteristic of mass mortalities during the summer. During growth experiments conducted by the School of Fisheries in these areas, one-year-old mussels began dying in June. High mortalities were also found by other researchers and people in the industry and entrepreneurs (a complete documentation is presented earlier in this report). In 1980 *Mytilus californianus* was introduced to local markets in competition with *Mytilus edulis*. At that time it was being harvested from the outer coast of Oregon and sold across the country. In addition, a preliminary growth experiment indicated that *Mytilus californianus*, when placed in productive inland waters, grew and survived well. Because of these encouraging results, researchers of the School of Fisheries felt that the culture of *Mytilus californianus* should be investigated further, and that it could possibly be grown where *Mytilus edulis* could not.

Experimental Set-up

To test its culture potential, *Mytilus edulis* and *Mytilus californianus* were grown side by side at two locations unsuited to *M. edulis* culture. One of the areas did not support adequate growth of *M. edulis*, and the other experienced mass mortalities. Growth, survival and seston measurements were taken to compare the two species. Specimens of *M. californianus* were taken from intertidal rocks of Tongue Point on the Strait of Juan de Fuca. Specimens of *M. edulis* were collected from the undersides of floating docks at Coupeville dock in Penn Cove on Whidbey Island.

Seven hundred individuals of each species were taken to be divided equally between the two test sites. Average size of mussel groups ranged from 13.7 to 15.1 millimeter in shell length. Mussels were placed in growth cages and submerged one meter below the surface from floating docks. Locations are as follows (Figure 10):

Area	Structure
Manchester	National Marine Fisheries Service floating docks
Squaxin Island	Salmon net pens on the east side of Squaxin Island

From March through November, 1981, mussels were removed from their cages monthly, separated, measured, and mortalities recorded. Missing or dead mussels were replaced. In addition, 10 mussels from each control group were taken for tissue and shell analysis.

Organic production of the two mytilid species were compared to evaluate their overall success as a population. As in any crop grown for eventual harvest, a larger yield is desirable. In this case the weight of organic compounds produced by each species were used as a comparative parameter. The values obtained, called the Total Organic Production (TOP), were calculated by ashing the mussels in a muffled furnace and using the difference in the weights before and after ashing as the organic value. An organic value was then calculated for the experimental mussel population by multiplying the number of survivors in each group by

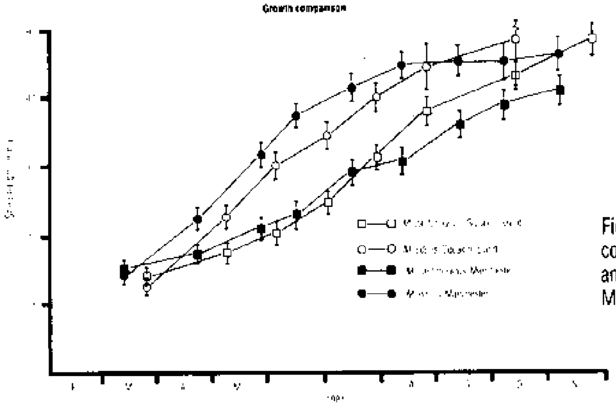


Figure 27. Shell length growth comparison between *Mytilus edulis* and *Mytilus californianus* grown at Manchester and Squaxin Island.

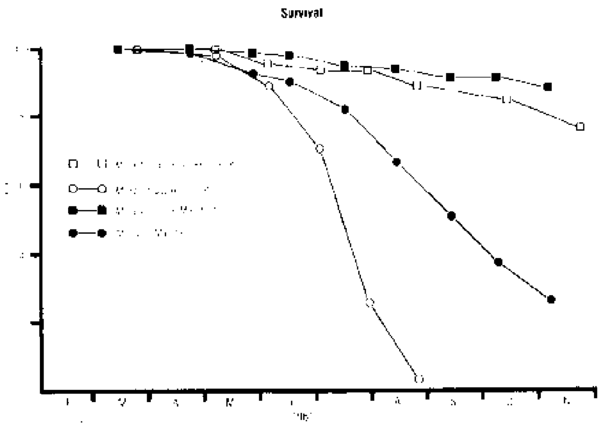


Figure 28. Survival of *Mytilus edulis* and *Mytilus californianus* grown at Manchester and Squaxin Island.

the average organic value of a mussel at the shell lengths calculated at each sample period. The TOP value obtained is essentially an estimate of the organics that were accrued by the population of 100 mussels, taking into consideration loss of organics from mortalities.

At both sites the amount and types of particulate material in the water available as food to mussels was sampled. Samples were taken using the methods described by Strickland and Parsons (1972) for determining the weight of microscopic materials in seawater.

Results

Shell Lengths Shell length measurements revealed that at both sites, ***M. edulis*** initially grew faster for the first three months, but by August growth of ***M. edulis*** began to slow down (Figure 27). By the termination of the experiment the difference in size between the two species was small. Average shell lengths and 95 percent confidence intervals are as follows:

	Squaxin Island	Manchester
M. californianus	47.8 mm + 1.59	40.6 mm + 1.48
M. edulis	48.3 mm + 7.6 (8 months)	45.6 mm + 1.65

Survival Survival was similar at both sites but dissimilar between species (Figure 28). ***M. californianus*** showed low mortality throughout the experiment and at no time did many die at once. ***M. edulis***, on the other hand, only survived well until June, when mortalities began to appear and increased until, by September, there was only one survivor remaining at Squaxin Island and only slightly more than 20 percent at Manchester. Predators were not a factor in either location as the mussels were grown in flow-through cages and at no time did the presence of common mussel predators become apparent. At times of mortalities freshly dead mussels could be found gaping open with the partially decayed tissue still in the shell.

Total Organic Production Growth of bivalve populations have often been expressed as increases in shell dimensions. Though this gives insight to shell growth, it adds no understanding of a species' ability to utilize its environment, fix carbon containing energy substances, and survive. TOP values were used in this study to supplement shell-length comparisons. In the first two months of growth, ***M. edulis*** had accumulated a higher TOP value at both sites, but in June and July, because of substantial mortalities, they began to drop (Figure 29). Conversely, TOP values for ***M. californianus***, during the same period, began a rapid upswing at both loctions, and attained the highest TOP value of 125 grams per 100 mussels.

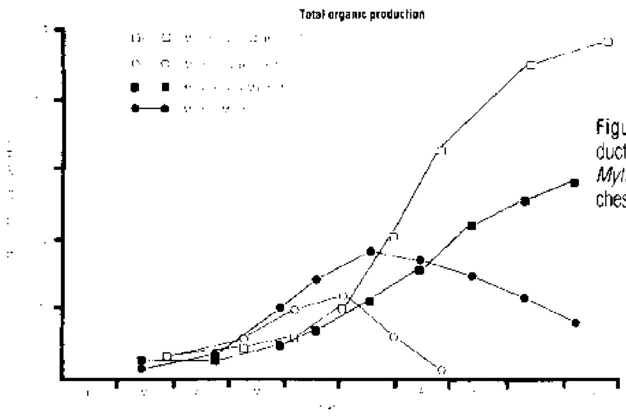


Figure 29. Total Organic Production (TOP) of *Mytilus edulis* and *Mytilus californianus* grown at Manchester and Squaxin Island.

Seawater Analysis Squaxin Island and Manchester have substantial differences in water productivity: Squaxin Island is by far the more productive. Its waters are very green and it is possible to see planktonic cells in the water at times. During the spring and summer there are definite phytoplankton blooms that make the water turbid and rich looking. Manchester, on the other hand, has very little phytoplankton in the water. For most of the year, it is clear and nonproductive. During the summer some large blooms appear, but they often disappear as fast as they come. Figure 30 shows the total weight of seston, POM in grams, and the average particle sizes for seawater at Manchester and Squaxin Island. At Squaxin Island there was more total seston, and therefore more particulate organic matter, which meant more food was available for filter feeders. This may be responsible for growth differences observed between the two sites.

Culture Potential of *Mytilus californianus*

Harvesting of ***Mytilus californianus*** from the outer coast of Oregon and its successful introduction to several western markets lends credence to the potential marketability of this organism if cultured. Since some areas in Puget Sound cannot support culture of bay mussels, the California mussel may be a suitable alternative.

Although ***M. edulis*** grows faster than ***M. californianus***, both reach a harvestable size in approximately one year (Chaves, 1975; Chaves and Chew, 1975; Johnson and Chew, 1982; Skidmore, 1983; Incze and Lutz, 1980). Dry tissue weights for a 50-millimeter ***M. californianus*** are slightly greater than ***M. edulis*** indicating that a higher meat yield after cooking is obtained for ***M. californianus***, which is a desirable trait to a restauranteur. Shell weights of cultured ***M. californianus***, however, are nearly twice that of cultured ***M. edulis***, but this may be an asset because it may allow for mechanical cleaning. Penn Cove mussels are presently stripped from culture lines, separated, and cleaned by hand. The shells of ***M. edulis*** are so brittle that mechanical cleaning would cause too many shells to be broken.

A culture species that experiences 100 percent mortality before it reaches harvest size is obviously unacceptable. At Squaxin Island, an entire experimental population of ***M. edulis*** died by the end of the summer. However, ***M. californianus***, grown at the same site in the same manner did not experience the high mortality. Seventy-seven percent of the popula-

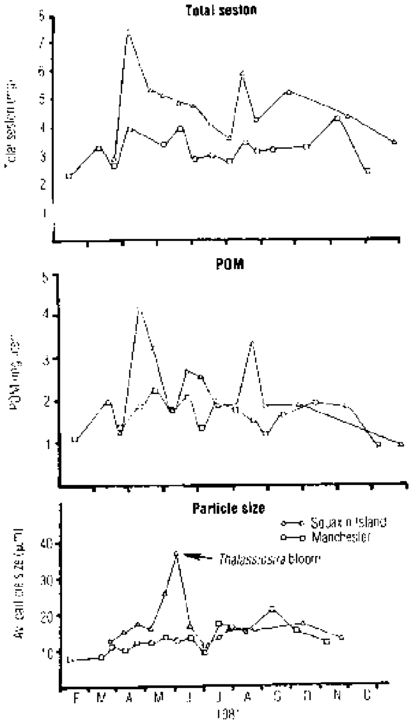


Figure 30. a) Total seston, b) Particulate Organic Matter, and c) average particle sizes for seawater at Manchester and Squaxin Island.

tion survived, indicating the possibility of *M. californianus* culture in south Puget Sound

Another indicator used in this study was Total Organic Production (TOP), which assesses survival rates of the two species while weighing total growth of mussels as the amount of organic compounds accrued. High TOP values attained by *M. californianus* indicated that it was the more productive of the two species in a culture situation.

Despite the overall biological attributes of *M. californianus* and its culture potential, there are some problems to be considered. Mussel culture is dependent upon catching natural settlements of wild larvae. Gathering *M. californianus* seed is not yet feasible, because its sporadic spawning characteristics do not result in massive settlements of larvae like those of *M. edulis*. Hatchery-produced seed would be mandatory to culture *M. californianus*, which may make it economically unfeasible compared to *M. edulis* because of the high capital outlay required for seed.

Another factor is market acceptance of cultured *M. californianus*. Although California mussels have been sold in local markets, it was when locally cultured *M. edulis* were not widely available so their ability to compete is unknown. *M. californianus* has a slightly iodine aftertaste and its meat is off-white to deep orange in color. Females are orange due to the bright orange color of ripe eggs. Males generally have lighter-colored meat. Some local restauranteurs prefer the white creamy appearance of "fat" *M. edulis*, but even though the sale of cultured *Perna canaliculus* from New Zealand has not been hampered by orange-colored meats, differences in flavor and appearance could affect the marketability of California mussels in a highly competitive marketplace.

Hatchery Experiments with *Mytilus californianus*

The feasibility of culturing *M. californianus* in Puget Sound pivots on the need for hatchery production of its seed. The technology to rear large batches of California mussel larvae is being pursued and is close at hand. Many factors, both economical and biological, need to be addressed to adequately assess its potential. It was the aim of this study to determine whether culture of *M. californianus* in Puget Sound is feasible. At this point, culture feasibility depends upon successful manipulation of large batch larval experiments.

Because *Mytilus californianus* is relatively new to shellfish hatcheries, optimal rearing conditions have yet to be determined. From 1981 through 1983, Falmagne (1984) worked on finding optimal temperatures and salinities for rearing the larvae of *M. californianus*. She experimented with different techniques to enhance the rearing and settlement of larvae in hatchery conditions at the University of Washington shellfish hatchery at the National Marine Fisheries Service aquaculture facility and the Environmental Protection Agency laboratory at Manchester.

A wide range of temperatures and salinities were tested to identify the environmental conditions that can support the growth and survival of *M. californianus* larvae (Falmagne, 1984). A grid type of experiment was conducted to note growth and survival of larvae with varying temperature and salinity combinations.

Spawning of the Animals

Coaxing *M. californianus* to spawn was not difficult. Out of 22 spawning attempts, 18 were successful. To initiate spawning, mussels were placed in seawater at 18–20°C. Males would most often be the first to start spawning and the sperm in suspension would initiate the females to spawn. The best spawning occurred when the mussels were left out of the water for 24 hours. Mussels between six and eight centimeters in shell length were the most reliable spawners. Females produced from two to twelve million eggs per spawning.

Placing mussels to be spawned in a concentrated agal bath also enhanced success in spawning (Breese, personal communication, in Falmagne, 1984). The agal bath consisted of concentrated monocultures of *Tisochrysis paradoxa* or *Pseudoisochrysis paradoxa* that had the pH adjusted between 8.5 and 9.5. Nine out of ten spawnings were successful with this procedure.

Rearing Larvae

Bacterial infestation was apparent with cultures at 18°–20°C. To help control this problem the water in culture tanks was changed daily. No antibiotics were used but the tanks were scrubbed with chlorine every other day and rinsed with hot tap water. Larvae were fed daily in the morning and afternoon. Instant Ocean salts were used to attain seawater salinities that were greater than the ambient water salinity. The effect of adding Instant Ocean salts on the survival of larvae was tested, and found to have no effect.

Results

Embryos and larvae were reared in a factorial experiment using eight temperatures and six salinities. Temperatures ranged from 4.0°C to 25.0°C at 3° intervals, and salinities

Table 7. Optimal temperatures and salinities for survival of *Mytilus californianus* larvae.

	Temperature	Salinity
Embryonic	14.5	29.8
Day 3	15.5	30.7
Day 7	16.1	39.3
Day 17	14.7	30.6
Day 21	14.7	30.1

Table 8. Optimal temperatures and salinities for growth of *Mutilus californianus* larvae.

	Temperature °C	Salinity °/oo
Day 3	15.9	30.8
Day 7	17.9	31.2
Day 17	14.3	31.2
Day 21	14.5	31.1

ranged from 26°/00 to 36°/00 at 2°/00 intervals. Survival and growth of larvae were measured at days 3, 7, 17, and 21. Greatest survival rates at each sampling are shown in Table 7.

M. californianus larvae survived best at 14.7°C and a salinity of 30.1 ppt for the 21-day experiment. Figure 31 shows a response surface for survival at the 21-day sample: the center is the optimal temperature and salinity for survival to day 21. The center was considered as having induced 100 percent survival and the temperatures and salinities corresponding with the rings around the center induced survival of larvae, as indicated on the rings.

Larval growth was also affected by differences in temperature and salinity, temperature especially. Temperatures and salinities that induced the best growth are shown in Table 8; growth response surface is shown in Figure 32.

Similar trends emerged in both survival and growth by varying temperatures and salinities. In both cases faster growth and better survival was apparent at higher temperatures when the larvae were young (3–7 days) and as the larvae became older (17–21 days) the trend reversed and the larvae were enhanced by lower temperatures.

Settlement

In Falmagne's experiments, the *M. californianus* larvae were ready to select a site in which to settle at 17–24 days from fertilization. This was marked first by the development of a conspicuous "eyespot" and finally a ciliated foot. Like many other bivalve larvae, the development of an eyespot indicates the approaching settlement from the free-swimming stage. Just before a settlement the ciliated foot appears (at this point the larvae is termed "pediveliger," which is used in the search for a site on which to settle. Eyespots developed when the larvae were 230–240 micrometers in size and larvae remained approximately this size until settlement. When the larvae settle, they attach themselves with a byssal thread.

Metamorphosis of *M. californianus* from free-swimming larvae to that of sessile, attached mussels has been the most plaguing factor in attempts to "set" larvae. Larvae survived to near the time of metamorphosis, at which point substantial mortalities occurred. During metamorphosis larvae lose their velum (a ciliated circular organ used for swimming and feeding) and begin life as attached organisms. No feeding occurs during metamorphosis; energy required for physiological rearrangement comes from stored energy reserves which are lipids. If the lipid level is low, the larvae may not survive (Gallager and Mann, 1981).

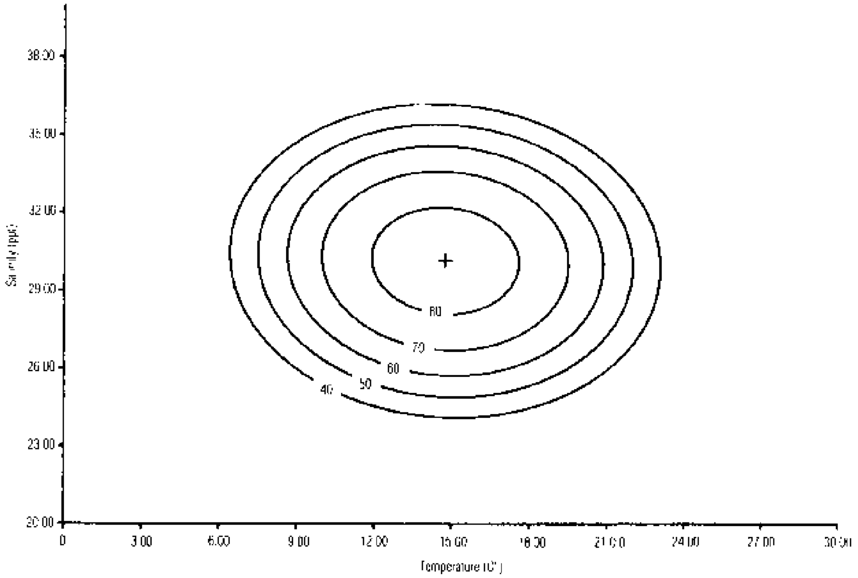


Figure 31. Surface response of *Mytilus californianus* larval survival. Optimal survival occurred at center where Temp. 14.7°C and salinity 30.1 ppt. to day 21.

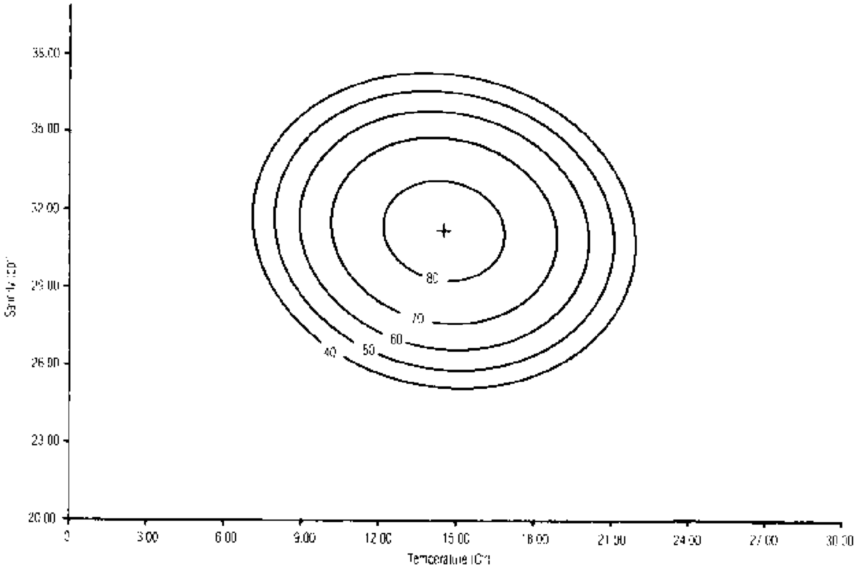


Figure 32. Surface response of *Mytilus californianus* larval growth after 21 days of hatchery culture. Optimal growth occurred at center where Temp. 14.5 C° and Salinity 31.1 ppt.

Once the metamorphosis is complete the mussels again begin to feed.

Settlement attempts have thus far met with limited success. Many techniques and different substrates have been used to increase the numbers of larvae settling. However, in most attempts the final number of settled larvae were unacceptably low.

Several attempts were made to enhance the settlement. *M. californianus* was found to prefer the same filamentous type collector substrates that *M. edulis* preferred. Figure 33 shows that, of the three substrates available for *M. californianus* to settle on, it chose rubberized curled packing hair, which was the most filamentous.

A peculiar trait that *M.californianus* displayed when searching for a settlement site was their habit of dropping to the bottom of the tank. Most of the pediveligers could be found at the bottom of the tank. When collector substrates were suspended in the tanks most of the settlement would occur toward the bottom of the substrate.

Other techniques used to enhance settlement were conditioning the water by placing adult mussels in it before introduction of the larvae and by decreasing the temperature of the water during settlement attempts. The most significant effect was induced by lowering the water temperature, one degree per day, to 12°C. Survival of larvae after metamorphosis was best using this procedure.

Experiments to determine lipid reserves by staining (Gallager and Mann, 1983) and to develop new techniques to enhance settlement are under way. These experiments may shed light on the reason for high mortalities of larvae during metamorphosis. If the cause is low lipid reserves, then techniques to alleviate this problem can be researched.

Biological Considerations

Introduction of exotic species in Puget Sound is not a new occurrence. In 1924 the seed of the Pacific oyster (*Crassostrea gigas*) was introduced to Puget Sound to aid the failing and over-harvested Olympia oyster. Not only did the Pacific oyster adapt well on the west coast of the United States, so did some associated plants and animals were introduced along with the oyster shipments. For example, Japanese littleneck clams (*Tapes japonica*), now commonly found on many south Puget Sound beaches and highly desirable as a commercial species, was introduced along with a troublesome gastropod, *Ocenebra japonica*, the Japanese oyster drill. Both species have had an economic impact in Puget Sound, one positive and one negative. Thus, introduction of non-native species, such as *M. californianus* is approached with great caution. While the exact outcome of transplanting *M. californianus* into Puget Sound is not known, possible adverse effects should be considered.

Johnson (1981) noted the following considerations when evaluating the potential outcome of introducing *M. californianus* into Puget Sound aquaculture:

1. The range of *M. californianus* extends along a major portion of the Pacific coast of North America. Harger (1970b) states that it does not generally inhabit protected waters, but does occur sparsely in harbors, thus *M. californianus* may not be successful in Puget Sound. However, this may be an oversimplification since its culture here may overcome the mechanisms that exclude its colonization.

2. *M. californianus* grown in simulated culture conditions grows well and survives in areas where *M. edulis* does not. Well-developed eggs were observed under microscope in a sample of *M. californianus* from Squaxin Island. The above findings suggest that the conditions in Puget Sound are not limiting to the reproductive capabilities of *M. californianus*.

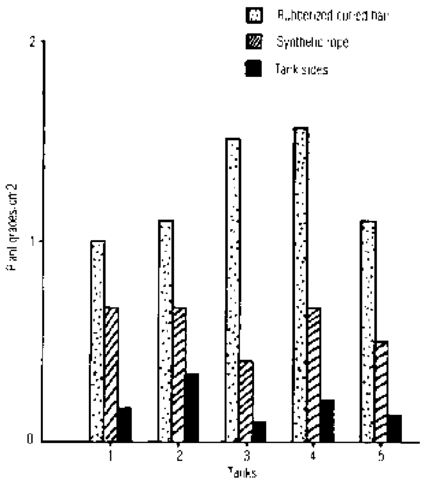


Figure 33. *Mytilus californianus* larval settlement on two types of collector substrates and tank sides.

3. If it is possible for *M. californianus* to spawn in Puget Sound, the next consideration is whether the larvae can survive and settle. Very little information is available on preferred substrate and larval behavior. The University of Washington Sea Grant supported hatchery at NMFS aquaculture facility in Manchester has been unable to successfully rear a large batch of larvae past metamorphosis. Possibly conditions in Puget Sound limit the range of *M. californianus* by exclusion of the larvae.

Reproductive strategies between mussel species are quite different. *M. edulis* is a mass spawner, releasing large numbers of eggs in the spring. *M. californianus* appears to be a trickle spawner with no predictable pattern of spawning seen. Competition for space in Puget Sound is keener because of reduced wave action, so spawning characteristics of *M. californianus* may not be a successful survival strategy. Its "trickle" spawning characteristics introduce only low numbers of larvae into the ecosystem compared to *M. edulis*, thus it depends upon availability of suitable sites and colonization of space would be minimal.

4. Assuming that *M. californianus* spawns and its larvae survive and settle, their eventual success or failure will depend on competition with other species, especially *M. edulis*. Its success will be dictated by its suitability to cope with its environment and its vulnerability to predators. It is possible that it can survive in some areas and not others due to the large environmental differences throughout Puget Sound.

Harger (1968, 1970a, b, and c, 1972a and b) performed many studies on the interactions and coexistence of the two mussel species in southern California. He found that *M. edulis* maintained a competitive advantage over *M. californianus* in quiet water situations because of its crawling behavior. *M. edulis* crawls to the outside of a clump, leaving *M. californianus* on the inside thereby restricting its growth and eventually smothering it in silt. In the exposed environments of the open coast *M. californianus* holds the advantage by its ability to remain attached during severe winter storms. *M. edulis* is more susceptible to predation and wave force.

5. Three means of exclusion of *M. californianus* from Puget Sound must be as-

sessed to evaluate the consequences of its introduction: competition with *M. edulis*, specificity of settlement sites, and larval dispersion. As mentioned earlier, competition between the two species tends to favor *M. edulis* in quiet waters. This may be why *M. californianus* has not established itself in Puget Sound. However, Petrailis (1974) has suggested that *M. californianus* is quite selective in choice of settlement sites, unlike *M. edulis* which may settle on almost any substrate. Juvenile *M. californianus* are often found in the byssal fibers of the adults (Suchanek (1978)). If *M. californianus* settles only on byssal fibers or typical outer coast substrates, then the lack of suitable settling sites may limit their extension into Puget Sound (Petrailis 1974).

The net outflow of surface waters in Puget Sound and the Strait of Juan de Fuca may also limit *M. californianus* to the outer coast by preventing introduction of larvae into Puget Sound. Although at times water flow may bring some *M. californianus* larvae into Puget Sound, low numbers may preclude colonization. Two or three of these hypotheses together may account for the *M. californianus* population decreasing from the mouth of the Strait of Juan de Fuca to Port Townsend.

Conclusions

The risks involved in introducing *Mytilus californianus* into Puget Sound are not clearcut. Favoring its success are the observations that it grows and survives well and produces ripe spawnable eggs when raised in Puget Sound. Its larvae survived in temperatures and salinities in the hatchery which are not uncommon in Puget Sound, although the larvae did not survive past metamorphosis. Conversely, evidence also indicates that *M. californianus* might not survive in Puget Sound. Intertidal regions of bays and estuaries throughout its range have not been substantially colonized. Harger (1970c) suggests that in a quiet environment *M. edulis* holds the competitive advantage over *M. californianus*.

4 ADDITIONAL CONSIDERATIONS

Socio-political Aspects (Permits and Leases)

Before an aquaculture structure can be legally placed in the water several requirements must be met. First, if the area to be used is not privately owned, use of the land must be secured in the form of a lease from the Department of Natural Resources (DNR). DNR manages many beaches owned by the State of Washington and subtidal bedlands below the line of extreme low tide, −4.5 feet. A floating aquaculture structure anchored to the bottom requires a lease of the seafloor under the structure. Generally, a full fair market rental value is assessed; however, minimum lease fees can be arranged for an experimental-phase commercial project.

Washington's Shoreline Management Act of 1971 gave local governments jurisdiction over their aquatic shorelines, which means that counties and incorporated cities have the right to grant or deny the use of their shoreline waters for aquaculture purposes. When an application for permit is submitted to a local planning department it is reviewed on many levels. Many local planning departments have, or are writing, a Shoreline Master Plan that designates areas for aquaculture compatible with other upland and water uses. The Shoreline Master Plan also considers biological, environmental, and physical factors that may effect different aquaculture structures. The county or city evaluates the aquaculture proposal in terms of adherence to the Master Plan's policies and designated areas.

Local county planners also weigh heavily the opinions of shoreline residents who may believe a proposed aquaculture facility will ruin their view, smell bad, or threaten their quality of life. The permit process includes a public hearing open to anyone with concerns, questions, or opinions about the proposed aquaculture activities. During past permit evaluations concerned citizens have wielded considerable influence on the outcome of the hearings. In some cases citizens have blocked a permit and created an atmosphere in which future permit applications for that area would be similarly thwarted. Many aquaculture proposals have met with such opposition.

Decisions rendered by local government can be appealed to the Shorelines Hearing Board, created by the Shoreline Management Act of 1971. The Shorelines Hearing Board has the authority to overturn a decision made by the local government, if it deems it appropriate.

There are other agencies that also review permit applications. The Army Corps of Engineers regulates all navigable waterways, and requires a permit for any structures such as rafts, floats, longlines, stakes, or anything obstructing the water surface or column. The Washington Department of Fisheries (WDF) is responsible for managing shellfish stocks, and must provide written authorization to allow any transfers of seed stock or adult shellfish from other areas, states, or countries. The State Environmental Protection Act of 1976 (SEPA) requires that environmental consideration be given by state and local governments in the decision-making process for shoreline permits. SEPA guidelines have been established to determine when an environmental impact statement (EIS) is needed (Magoon and Vining, 1980).

Predators

Predators that consume mussels can cause substantial losses to mussel culturists. The most common predators are scoter ducks, starfish, and crabs.

Scoter Ducks

Diving ducks, especially scoters, are the most troublesome of the mussel predators. Three species of ducks are responsible for the majority of the losses:

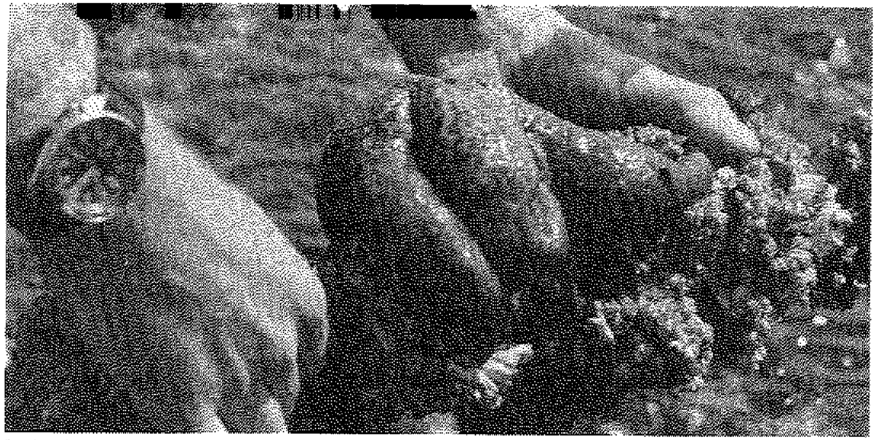
1. Surf scoter (*Melanitta delgandi*),
2. White-winged scoter (*M. perspicillata*), and
3. Black scoter (*Oidemia americana*).

When these ducks feed on culture lines, they dive underwater and remove clumps of mussels. Returning to the surface, they shake the clump, dislodge one mussel and swallow it whole and let the loose mussels sink to the bottom. Scoters can completely strip lines of seed and harvest-sized mussels.

Scoters are migratory birds, appearing in Washington in late summer and fall. Their main diet in Puget Sound seems to be mussels and clams. When flocks of from several hundred to thousands of scoters appear, they locate natural mussel beds, and dive on them to feed. Unfortunately, they also frequently locate mussel rafts or longlines and can inflict severe losses in a short time. They may even take up permanent residence in particularly good feeding areas, such as culture operations, and are hard to get rid of once settled.

Many techniques have been tried to scare or drive scoters away from aquaculture sites. The most common and successful method used by mussel farmers at present is the .22 caliber rifle. Shots aimed near a flock of ducks will generally frighten them away for a short time, but invariably they return within an hour or less.

More sophisticated techniques have met with varying results. Scarecrows, loud noises, even kites resembling their natural predator, the eagle, frighten them at first, but within several days the scare techniques seem to have little or no effect. At present, various underwater sonics are being tested by researchers at the University of Washington to scare the ducks in their possibly most vulnerable state, underwater.



Starfish feeding on *Mytilus edulis.*

Starfish

Starfish consume mussels and other shellfish as part of their normal diet. In Washington the use of rafts and floats for mussel aquaculture deters large starfish from reaching culture lines, but it is possible for free-swimming starfish larvae to settle on culture lines. At Penn Cove Mussels, Inc., larval starfish (*Pisaster* or *Evasterias*) have settled on seed lines and consumed larger and larger mussels as they grew. The starfish seem to grow at the same rate as the mussels and in time could have potentially consumed all the mussels on the lines if they hadn't been detected.

Starfish control for bottom or intertidal mussel culture is an integral part of the operation. Small underwater fences have been used in some parts of the world to limit access of starfish to culture areas. In the Netherlands dredges remove starfish from bottom culture plots. In Washington, starfish are removed by hand at Race Lagoon mussels. In France, plastic is wrapped around the bottom of wood poles to deter starfish.

Crabs

Crabs can cause considerable damage to cultured shellfish crops, especially the red rock crab, *Cancer productus*. Red rock crabs consume mussels, clams, and other shellfish and debris on intertidal and subtidal beaches. The crab crushes the bivalve shell with its claw to consume the meat inside. At Race Lagoon Mussels, 2,500 pounds of mussels ready to be cleaned were placed for purging in large mesh net bags in the low intertidal zone. Within two weeks crabs had eaten 1,500 pounds of mussels, leaving the bags virtually empty and broken shells littered nearby.

Bottom and intertidal culture systems affected by starfish can similarly be affected by crabs. Effective measures to limit destruction are underwater fences and physical removal of predators. Unlike starfish, crabs can be a pleasure to dispose of, as one can cook and eat the spoils.

Weather (Windwaves and Exposure)

Locating an aquaculture facility in an area that is exposed at times of high winds may meet with uncertain success. Mussel rafts, longlines, intertidal systems, and shallow bottom culture plots are all vulnerable to waves created by wind. Steady pounding by waves can cause chafing of gear and loss of crop. Especially vulnerable are mussels approaching harvest size, because as they grow larger they tend to grow away from the culture rope and clump together, which causes them to be easily shaken off by wave action.

Most mussel culture structures in the state of Washington are located in protected coves and bays. Fortunately, *Mytilus edulis* grows quite well in protected coves. Growth rates are often increased by the higher temperatures and more productive waters found in Puget Sound bays and inlets. Unfortunately, the presence of pollution is often found in these same protected waters.

Pollution

Historically, the most significant impacts on shellfish culturing areas have been the result of discharges from urban sewage treatment plants, industrial waste, and contamination from marina activities. Beginning in the early 1980s, the pollution problem has been changing. Current problems do not stem from urban waste; rather they appear to be the result of nonpoint contamination in rural areas, which are also traditional shellfish culture areas.

Two types of pollution sources have been identified by the Washington State Department of Ecology (Saunders, 1984):

1. Point Source: Pipes or other conveyances that transport wastewater from an industrial or sewage treatment plant.
2. Nonpoint Source: Pollutants are washed off the ground surface into streams and bays or enter through groundwater transport. Sources are single-home drainfields or runoff from "hobby" grazing animal pastures.

Within the last three years, six areas have been closed totally or intermittently to commercial oystering due to bacterial contamination. Four of these six closures were the result of nonpoint contamination: Minter Bay, Burley Lagoon, Henderson Inlet, and Eld Inlet. The ten years prior had no pollution closures.

One of the point source contaminations occurred in Penn Cove in September 1983. High counts of coliform bacteria (fecal coliform and other pathogens come from the gastrointestinal tracts of warm-blooded animals) were found in water and mussel samples and the entire bay was closed. Closures occur when maximum permissible fecal coliform counts for shellfish tissue, 230 organisms per 100 grams, are exceeded. For water, the maximum count permitted is an average of 14 organisms per 100 milliliters with not more than 10 percent of the samples exceeding 43 organisms per 100 milliliters.

In Penn Cove the problem was blamed on a sewage treatment plant on the north side of the cove. After additional testing, the south side of the cove was determined to be clean and reopened for harvest. As of March 1985, the north side of Penn Cove was still closed.

The Department of Environmental Health in Olympia is responsible for certifying areas for harvest. If shellfish are found to be under the maximum levels permitted for fecal coliform and are found to be safe in all other chemical and biochemical aspects, the area can be certified for shellfish harvest. All shellfish harvesting operations must be certified. Generally, if a proposed shellfish operation is too close to a sewage treatment plant it will not be certified. However, the harvest of uncertifiable shellfish can sometimes still be undertaken if they are depurated.

If contaminated shellfish are "relayed" to a clean site for several weeks they can rid themselves of much of the coliform and other contaminants and be safe for harvest. Relaying of contaminated shellfish to a clean holding site is regulated and strictly enforced by the state Department of Environmental Health to ensure that the product that reaches the marketplace is safe for human consumption. Upon approval, shellfish can be moved to the depuration site and held for a two-week period, which will purge most contaminants. If tests show they are safe then they can be harvested.

Paralytic Shellfish Poisoning

Filter feeding shellfish such as clams, mussels, and oysters can accumulate toxins in their tissues by feeding on toxic algal blooms present in the water. Many species of free-swimming plankton on which shellfish feed can "bloom" and cause what appears to be a red tide. Only one of these species, *Gonyaulax catenella*, is known to contain a neurotoxin within its cells. When shellfish feed on a bloom of *G. catenella*, the toxins are concentrated in the shellfish. If humans or other mammals consume shellfish containing high levels of this neurotoxin, they may become ill or die from Paralytic Shellfish Poisoning (PSP).

The first symptoms of PSP are a tingling feeling in the fingertips and mouth, and can appear within minutes of eating the affected shellfish. These symptoms progress into the limbs and body and a feeling of numbness ensues. Coordination and speech can be affected and vision may be blurred. The final symptom is the cessation of involuntary muscles such as the diaphragm, used for breathing. A person significantly affected by PSP may have to be placed on an artificial breathing apparatus. Eventually the symptoms will go away but partial paralysis may persist for months or years.

The Department of Social and Health Services (DSHS) and county Public Health departments are responsible for monitoring levels of PSP in shellfish. Samples from many areas on the open coast and in Puget Sound are taken to the DSHS laboratory and are analyzed for toxin levels. If the toxin level exceeds 80 micrograms per 100 gram sample tissue the area is closed for sport or commercial harvest of shellfish. For commercial shellfish operations closed due to PSP, resumption of harvesting is permitted after two consecutive samples, taken at least a week apart, show less than 80 micrograms of toxin per 100 grams of shellfish tissue.

Laboratory analysis of samples is determined using a mouse bioassay. Shellfish are shucked and ground into a slurry, which is cooked in an acidic broth that allows the toxin to go into solution. The extract is injected into three mice which are observed for signs of PSP seizure or death. The time it takes the mice to die (last gasp for air) is used to calculate the toxin content of the sample. Though this seems like an archaic method in this age of high technology, because of the many complex toxins and proteins involved, a faster or more accurate test is currently not available.

At this writing, a potential method of controlling blooms of *G. catenella* in small bays is being investigated at the University of Washington. A parasite known to contribute to natural control of populations of *Gonyaulax* has been discovered. This parasite, another dinoflagellate (*Amoebophyra*) is under culture at this writing for testing. The parasite actually invades the *Gonyaulax* and takes over its chromosomes, eventually killing its host and giving off many spores to reinvade other cells. This work, funded by Washington Sea Grant, is being conducted by Louisa Nishitani and Dr. K. K. Chew at the College of Ocean and Fishery Sciences, University of Washington.

In 1978 red tide blooms occurred in Penn Cove, Saratoga Passage, and Holmes Harbor on Whidbey Island. Mussels, clams, and other affected shellfish were rendered extremely toxic for human consumption. Toxin levels of 32,000 micrograms per 100 grams of shellfish tissue were found in mussels from that area. This value far exceeds the toxin levels deemed by the Food and Drug Administration as safe for human consumption. Such levels could be lethal if one ate only a few mussels.

High levels of toxicity also cause the affected organisms to retain the toxin longer. Mussels have gained a reputation for picking up and losing toxicity rapidly. In 1978, butter clams, *Saxidomus giganteus*, retained toxin at unsafe levels for up to six months.

Fouling

The fouling of cultured mussels can be a considerable problem. Settlement of various species of invertebrates can add substantial weight to culture ropes in and out of water, and requires costly cleanup or removal at harvest. Some settlements of invertebrates can grow and actually start preying on the mussels, as mentioned earlier with starfish settling on mussel culture lines.

Johnson (1980) noted the types and amounts of fouling organisms found during different seasons at Penn Cove, Manchester, and Budd Inlet. These locations are summarized as follows:

Penn Cove

Fouling in Penn Cove varies with depth and season. Barnacles settle heavily in the spring and comprise up to 74 percent of the mussel weight over three months. Settlement of barnacles was greater at depth than near the surface.

Fouling during the summer was much lower than spring, only six percent of mussel weight. Surface mussels were more fouled than at depth. Few barnacles settled during this period but many other organisms were present: sea stars, polychaetes, nemertean worms (ribbon worms), sea cucumbers, hydroids, flatworms, and bryozoans. The largest settlement of invertebrates during early summer was that of mussels. Mussel larvae settled on the culture lines on and between the larger mussels. Small mussels fouling the culture lines can cause a considerable increase in the amount of time required to clean the mussels for market.

Manchester

Manchester received the least amount of fouling of cultured mussels. Seven percent of mussel weight was the highest recorded weight of fouling organisms found there. Seasons were significantly different and depths were slightly different. Fouling was the heaviest at two-meters during the spring, because of barnacle settlement. Bryozoans comprised the major portion of the fouling community during the summer. Although the weight of bryozoans was low their fouling was more significant here than at the other two stations, covering up to 50 percent of some mussels at the surface. Other organisms of the fouling community at this station were polychaetes, green algae, hydroids, ascidians, flatworms, and anemones.

Fouling of mussels on ropes in the intertidal zone by barnacles.

Budd Inlet

An intense settlement of barnacles was seen at Budd Inlet as at Penn Cove. It comprised the major portion of fouling weight during spring (nearly half the weight of the culture string was fouling organisms). Fouling weight during the summer was only two percent compared to 99 percent in the spring. Fouling was low during the autumn with the fouling organisms comprising a maximum of seven percent of the mussel weight. The fouling community during the summer and autumn included polychaetes, nemereans, flatworms, hydroids, barnacles, bryozoans, and anemones.

Effects of Intertidal Conditioning on Raft- or Longline-Grown Mussels to Cold Storage Survival

Raft- or longline-grown mussels are a high quality product, but because they are continuously submerged while growing, when out of water they have a relatively short shelf life. Proper handling and storage of mussels increases shelf life (Slaby and Hinkle, 1976), but "hardening" of mussels can also benefit shelf life. A common practice in the oyster industry is to place oysters in the intertidal zone where they are left exposed to air part of the day. This process is referred to as "hardening" and is used to increase the oysters' ability to remain closed while out of the water. If an oyster or mussel cannot remain closed, the liquor within the shell is lost and the animal soon dies.

Shelf Life of Intertidal and Continuously Submerged Mussels

Preliminary experiments comparing the survival of intertidal mussels gathered from floats and subtidal mussels (gathered from one foot above mean lower low water) show that intertidal mussels have a far better shelf life (Johnson, 1981). Mussels were placed in a refrigerator held at 1–4°C. Intertidally grown mussels remained alive far longer than continually submerged mussels, which began to die at day 6 while intertidal mussels did not begin to die until day 11 (Figure 34). Average survival time was 13.6 days for subtidal mussels and 19.3 days for intertidal mussels.

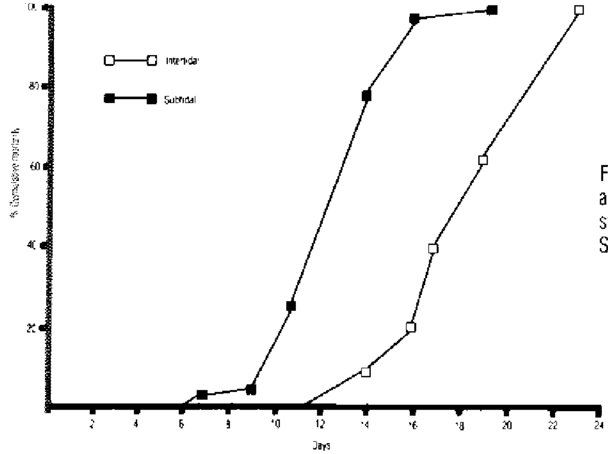


Figure 34. Mortality of subtidal and intertidal mussels held in cold storage (approximately 34°F, static). Subtidal N 73, Intertidal N 51.

Effects of Intertidal Hardening on Shelf Life

In June 1981, subtidal mussels were placed at the National Marine Fisheries Service Aquaculture Facility at Manchester. Some mussels were placed in baskets suspended from the pier at approximately six feet above MLLW and some subtidally. After 2, 9, and 16 days of intertidal exposure, the mussels were placed in a cold room and survival monitored (Table 9). Longer intertidal exposure did not necessarily produce longer mean survival. With 16 days of exposure an increase in the shelf life over the subtidal control was seen. However, there was only a 1½ day increase—not an appreciable advantage considering that up to 50 percent of the mussels in both intertidal and subtidal groups died in the hardening process.

A second experiment in September was performed to test the effects of intertidal height and exposure time on the cold storage survival. Mussels were placed at –2, 2, 4 and 6 feet above MLLW, which is 0, 18, 26 and 47 percent exposure to the air. Survival in cold room storage was unaffected by different tidal heights at which they were held (Table 10). Mortalities during the hardening period were also low, ranging from 7–13 percent.

Because there are only marginal gains in shelf life, hardening of subtidally grown mussels in Puget Sound appears to be an unlikely prospect. The benefits of a 1½ day shelf life increase is outweighed by the losses of up to half the population. Perhaps longer hardening periods are needed to substantially increase the shelf life of subtidally grown mussels.

Table 9. Mean cold room survival of mussels hardened at 6 feet above MLLW for 2, 9 and 16 days.

Exposure time	Mean survival (days)
0	7.9
2	9.4
9	7.0
16	10

Table 10. Mean cold storage survival time of mussels hardened at –2, 2, 4 and 6 feet above MLLW for 9, 16 and 23 days.

Exposure time	Intertidal height	Mean survival (days)
0		9.3
9	–2	9.5
	2	8.8
	4	10.7
	6	10.1
16	–2	9.2
	2	10.6
	4	9.2
	6	9.9
23	–2	11.2
	2	10.5
	4	10.8
	6	10.7

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