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Stock assessment and management frameworks for the proposed fishery for sea mussels (Mytilus californianus) in British Columbia

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Abstract

Sea mussels (*Mytilus californianus*) are the largest species of mytilid mussel. They are found only on the west coast of North America, and range from Baja California to Alaska. Sea mussels form dense beds, generally in the intertidal zone of exposed rocky shores. Sea mussels spawn throughout the year, with peaks in activity in the spring and fall. Fertilization is external, and pelagic larvae may spend 3-5 weeks drifting planktonically before settling to adult habitat. Growth rates are variable, depending on availability of food, intertidal elevation, temperature and mussel density. Sea mussels can grow to approximately 270 mm in length, and may live 50-100 years. Size at maturity is approximately 70 mm in length. Sea mussels are filter feeders, and are in turn preyed upon by sea stars, whelks, crabs, fish, birds and marine mammals.

Mussel beds are highly structured, and provide habitat for nearly 300 other species. If greatly disturbed or destroyed, mussel beds require many years (5-100+) to recover to the climax community. Rate of recovery is dependent on size of the disturbance, season of disturbance, intertidal elevation, substrate angle and intensity of larval recruitment.

A commercial fishery for sea mussels existed in Baja California, Mexico from 1967-1981. Mussel beds were quickly depleted, and the fishery was extended through discovery of previously unexploited beds until its collapse. A small fishery for sea mussels existed in Oregon from 1979-1997. Landings peaked in 1989 at nearly 30 t, but have since declined to <1 t. Reasons for the decline are unknown, but may include overharvest. Attempts to develop commercial fisheries for sea mussels in California and British Columbia did not succeed.

Programs to assess, manage and monitor proposed sea mussel fisheries are presented and evaluated. Because of the longevity of sea mussels, and the sensitivity of the mussel bed community to disturbance, very low harvest rates and specialized means of responsible harvesting are discussed. A preliminary survey protocol and suggestions for collecting fishery-dependent and fishery-independent information are provided.

Résumé

La moule commune du Pacifique (*Mytilus californianus*) est l'espèce la plus grande des mytilidés. On ne la retrouve que sur la côte ouest de l'Amérique Nord, de la Basse-Californie à l'Alaska. Elle forme des concentrations d'individus denses, généralement dans des zones intertidales rocheuses exposées. La moule se reproduit tout au long de l'année, mais avec des maximums de frai au printemps et à l'automne. La fécondation est externe et les larves pélagiques peuvent dériver pendant 3 à 5 semaines sous forme d'organismes planctoniques avant de se déposer dans l'habitat des adultes. Le taux de croissance est variable et dépend de la quantité de nourriture disponible, du marnage, de la température et de la densité des moules. Cette moule peut atteindre une longueur approximative de 270 mm et un âge de 50 à 100 ans. La taille à maturité est de 70 mm de longueur environ. La moule est un organisme filtreur qui est la proie des étoiles de mer, des buccins, des crabes, des poissons, des oiseaux et des mammifères marins.

Les lits de moules sont fortement structurés et constituent un habitat pour près de 300 autres espèces. Le rétablissement d'une communauté climacique peut prendre beaucoup de temps, de 5 ans à plus d'un siècle, après une forte perturbation ou une destruction des lits. La vitesse du rétablissement est fonction de l'envergure de la perturbation, de la saison où elle se produit, du marnage, de l'angle du substrat et de la vigueur du recrutement larvaire.

Une pêche commerciale de la moule commune a été effectuée en Basse-Californie (Mexique) de 1967 à 1981. Les lits ont rapidement été épuisés et la pêche s'est poursuivie, jusqu'à son effondrement, grâce à la découverte de lits jusque là non exploités. Une pêche limitée a été effectuée en Orégon de 1979 à 1997. Les débarquements ont atteint leur maximum, près de 30 tonnes, en 1989 avant de chuter à moins d'une tonne. Les raisons de cette baisse sont inconnues, mais peuvent inclure une surexploitation. Les tentatives faites pour mettre sur pied des pêches commerciales de la moule commune en Californie et en Colombie-Britannique ont échoué.

Les programmes d'évaluation, de gestion et de suivi de projets de pêche de la moule commune sont présentés et évalués. Étant donné la longévité de la moule commune et la vulnérabilité des communautés des lits aux perturbations, la discussion porte sur les très faibles taux de récolte et les méthodes spécialisées d'une pêche responsable. On trouve aussi un protocole préliminaire pour les relevés et des suggestions pour l'obtention de données dépendantes ou indépendantes des pêches.

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Introduction

Background

This paper was produced in response to a request by the Invertebrate Subcommittee of the Pacific Stock Assessment Review Committee (PSARC), the Federal/Provincial Seafood Diversification Committee (SDC) and the Vancouver Island Shellfish Cooperative (VISCO) to provide and evaluate potential assessment and management tools for development of a proposed fishery for sea mussels, *Mytilus californianus*[1], in British Columbia (B.C.). This paper follows a phase 0 review paper (collection and synthesis of information from the literature on the biology, assessment, management and fisheries history of sea mussels and their relatives in B.C. and elsewhere) by Schmidt (1999).

The objectives of this document are:

1) to review and supplement information and recommendations from the Phase 0 paper (Schmidt 1999);
2) to examine possible stock assessment and management frameworks which address Schmidt's recommendations and the concerns of the present author; and
3) to provide assessment recommendations and additional information for managers to consider as they formulate a management framework for the proposed fishery for sea mussels in B.C.

Sea Mussel Biology

The following summary relies heavily on information gathered by Schmidt (1999) in a formal phase 0 review, and review papers by Seed (1976), Shaw *et al*. (1988), Seed and Suchanek (1992) and Krause (1997). Additional information from other sources is cited separately.

Taxonomists currently recognize four extant species of *Mytilus*: *M. californianus* from the west coast of North America; and *M. edulis*, *M. galloprovincialis* and *M. trossulus*, all of which occur in both the Pacific and Atlantic Oceans (McDonald and Koehn 1988; Koehn 1991; McDonald *et al*. 1991; Gosling 1992). All four species occur in B.C.: the naturally-occurring bay mussel *M. trossulus* is common in protected waters, and the two exotic bay mussels, *M. edulis* and *M. galloprovincialis* have been introduced either for aquaculture purposes or unintentionally (Heath *et al*. 1995; Coan and Scott 1997; Suchanek *et al*. 1997).

Sea mussels are the largest species of *Mytilus*, attaining a maximum length of approximately 27 cm (Chan 1973; Paine 1976b). They are of typical mussel shell form, with an anterior umbone

[1] Harbo (1997) uses the common name California mussel for *Mytilus californianus*, and lists sea mussel and ribbed mussel as alternate names. Shaw *et al*. (1988) prefer the name California sea mussel, and list rock mussel, big mussel, California mussel and sea mussel as alternatives. I found it more convenient to use the name sea mussel in this paper, rather than refer to British Columbia California mussel fisheries.

and blue periostracum, which is often eroded in older animals. They are distinguished from other mytilids in possessing approximately 12 radial ribs, which run from the umbone to the posterior margin of the shell, and by having bright orange flesh. Sea mussels produce numerous pearls, either loose or as blister pearls, which are protuberances of nacre on the inner lining of the shell (Quayle 1978).

Sea mussels are distributed from Baja California to Southeast Alaska, generally inhabiting high energy, wave-swept rocky shores. The geographic distribution is limited by temperature extremes (cold in the north, warm in the south). Unlike bay mussels, sea mussels are intolerant of low salinity and siltation, and thus are confined to exposed coastlines. The two species exhibit distinct behaviours which account for different tolerances to siltation (Harger 1968).

Sea mussels form densely aggregated beds from the upper intertidal to subtidal depths. Mature mussel beds are spatially complex, often increasing in thickness from a single layer of mussels at the edge to several layers of mussels in the middle of the bed. Although beds are discrete, the range of bed sizes and their spatial arrangement in British Columbia has not been determined.

Adult mussels are attached to the substrate and each other by strong byssal threads. Although mussels can dissolve existing byssal threads and lay down new ones, mobility is low, limited primarily to expansion of bed margins: adult sea mussels are essentially sessile. Bed dimensions may be increased through limited movements of adults, or through displacement by crowding. Dislodged individuals may re-attach in the subtidal zone, but these individuals likely are not pioneers leading to the development of new subtidal beds. Populations are increased through successful settlement of new recruits and growth: exchange of adult individuals between distinct beds is not thought to occur.

The upper limit of the distribution is determined by the physiological tolerances of the mussels (temperature extremes, desiccation, length of time exposed during low tides). The lower limit of mussel distribution is thought to be determined by predation, and thus is dependent on the physiological tolerances of predators, primarily the sea star *Pisaster ochraceus* (Paine 1966, 1974, 1989; Robles *et al*. 1995). Sea mussels do form subtidal beds under special conditions, but intertidal and subtidal populations are not contiguous (Scagel 1970; Chan 1973; Paine 1976b, 1989). Because most beds are intertidal, and often the dominant feature of the preferred habitat, mussels are entirely available to either harvest or survey collection.

Schmidt (1999) suggested that current population levels could be considered essentially virgin, as no significant commercial fishery exists, or has existed recently, for sea mussels in B.C. There are limited harvests of sea mussels from the Port Hardy and Sooke areas to provide mussels for biotoxin monitoring programs (K. Schallie, Canadian Food Inspection Agency (CFIA), pers. comm.), but these are not considered to be significant.

The sexes are separate and fertilization is external. Gametes are liberated into the water column, and are likely short-lived (3-4 hr), limiting gene exchange through reproduction to relatively small areas (likely adults from the same bed, or from immediately adjacent beds). Sea mussels are trickle spawners, with some low levels of reproductive effort being expended throughout the year. Spring and fall peaks in spawning have been recorded in Oregon (Yamada and Dunham 1989) and elsewhere (Whedon 1936; Young 1942; Seed and Suchanek 1992). Spawning can be affected by ambient temperature and food ration, so spawning could have a stronger seasonal component in cooler BC waters than in Oregon or California.

Total fecundity is difficult to estimate in animals that spawn continuously throughout the year. It is safe to say, however, that sea mussels are extremely fecund, at least on the order of tens of millions of eggs. Fecundity is known to increase with size in other *Mytilus* species, and gonad weight increases exponentially with shell length in sea mussels (Suchanek 1981; Leigh *et al*. 1987).

Mussel larvae are planktonic for approximately 3-5 weeks, during which time they pass through several distinct stages (trochophore, veliger, conchiveliger and pediveliger) and finally settle as plantigrades. Sea mussel larvae have been reared to settlement in the laboratory in 17-24 days (Skidmore and Chew 1985; Falmagne 1984). Falmagne (1984) examined salinity and temperature tolerance of sea mussel larvae, and found reasonable survival between 13-19^{o}C and 26-34‰. Maximum survival was found at 28‰ salinity with temperatures of approximately 16^{o}C for the first 7 days, then decreasing to 14^{o}C prior to metamorphosis.

Because of the duration of the larval period, mussel larvae could potentially drift far from their natal bed, and this larval drift likely provides genetic mixing between beds (Widdows 1991). Dispersal of larvae is thought to be determined by the prevailing current structure at the time of spawning.

Because spawning occurs throughout the year, recruitment is also possible throughout the year. Several authors have described seasonal recruitment of sea mussels beginning in winter and becoming more conspicuous in midsummer (Paine 1974; Seed and Suchanek 1992; Robles *et al*. 1995).

Peterson (1984a,b) demonstrated that sea mussel pediveligers settle preferentially on spatially complex substrates, including clumps of adult bay mussels and the algae *Endocladia muricata*, but can settle on a broad range of substrates Petraitis (1978) demonstrated that juvenile sea mussels were more abundant in clumps of adult sea mussels. It is unclear whether this distribution is the result of selective settlement or differential mortality, but it is clear that the structural protection provided by existing beds of adult mussels is required for successful recruitment. Because settlement rates are lower and/or mortality rates higher on bare rock, areas which have been cleared require extensive time periods (5-100 years) to re-establish mussel populations. Available information on recruitment rates of sea mussels generally indicate a pattern of years of low recruitment that are occasionally punctuated by episodes of high recruitment (Dayton 1971; Paine 1974, 1976a; Seed and Suchanek 1992; Robles *et al*. 1995).

Growth rates are known to vary with food availability, degree of exposure (tidal height, and thus time available for feeding) as well as with degree of competition for food. Dahlhoff and Menge (1996) found that differences in food availability at two sites had the most significant effect on sea mussel physiological processes in Oregon.

Given adequate food ration, temperature becomes an important determinant of growth rate in mussels (Elvin and Gonor 1979; Jamieson 1989). Coe and Fox (1942, 1944) indicated that optimal growth temperatures for *M. californianus* are between 15 and 19°C, and that growth declined sharply above 20°C and below 14°C. Thus, in southern California, growth is most rapid in the cooler months, and slows or may stop in midsummer (Shaw *et al*. 1988).

Growth rates are dependent upon intertidal elevation, as this is highly correlated with exposure time, and thus time available for respiration and feeding (Dehnel 1956; Harger 1970). Crowding and competition for food affect growth rates of mussels within the same bed: individuals at the edge of patches grow more quickly than those in the center of patches. Overgrowth by algal epiphytes was found to decrease rates of growth and reproduction (Dittman and Robles 1991).

Coe and Fox (1942, 1944) and Fox and Coe (1943) recorded maximum sizes of subtidally suspended sea mussels in southern California to be: 80-86 mm (1 yr), 120 mm (2 yr), 140-150 mm (3 yr). Mussels that started at lengths <30 mm averaged between 3.75-5.00 mm/month growth, those between 40-70 mm averaged 2.67-3.83 mm/month, and those >70 mm averaged 1.17-2.00 mm/month. Maximum recorded intertidal growth rates from Oregon were approximately 2 mm/month (Yamada and Peters 1988; Yamada and Dunham 1989). Because temperature is an important determinant of growth, growth rates are expected to less in B.C.

Size at first maturity (spawning) for *M. californianus* in southern California was estimated to be 70 mm (Coe and Fox 1942), although gonad differentiation began at sizes of 25-30 mm (Whedon 1936; Coe and Fox 1942; Robles *et al*. 1995). Males began gonadal development at approximately 25 mm, and females at approximately 38 mm (Whedon 1936). The smallest animal Young (1945) was able to induce to spawn was 55 mm in length. It is therefore reasonable to assume size at first spawning for local populations to be at least 70 mm, until evidence to the contrary is found.

Natural spawning cues are not well known. Mussels have been induced to spawn in laboratory conditions using rough handling; periods of dry storage at low temperatures; excision of ripe gonads and placement in sea water; electrical stimulation; exposure to KCl, NH_4Cl, NH_4OH or $BaCl_2$; sudden increases in temperature; increased food ration; exposure to UV treated seawater; or exposure to kraft mill effluent (Shaw *et al*. 1988). Sea mussels were more difficult to induce than bay mussels, but could be induced through mechanical stimulation (scraping of the shells); pulling the byssus; or exposure to spawn, spawning mussels or macerated gonadal tissue (Breese *et al*. 1963).

As with most species, mortality rates are not constant throughout the life span of sea mussels. They are probably highest during the planktonic larval stage and immediately after settlement. Larger mussels have either grown through a size threshold which render them immune to predation by starfish, have shells thick enough to discourage predation by gastropods, or have attached high enough in the intertidal to effectively avoid predators (Paine 1976a). In the absence of disease, mortality amongst large mussels is infrequent, primarily due to episodic disasters (shear forces from large waves, wave-propelled logs and debris, or exposure to extreme temperatures at low tide) which remove portions of beds and create patches of exposed substrate (Paine 1976a; Paine and Levin 1981; Robles *et al*. 1995). Although some of these events (storms, temperature extremes) are climatic in nature, they are essentially unpredictable.

Settlement or mortality rates of recently settled mussels may be more susceptible to environmental influence. However, given the postulated population structure (extreme longevity and numerous age classes) and recruitment patterns (extended periods of low recruitment punctuated by few episodes of massive settlement), declining trends in recruitment would be difficult to detect, even over the long term. Because adult mussels are sessile, and thus cannot migrate in response to environmental stresses, changes in distribution are purely a function of either increased adult mortality (short-term) or decreased settlement and senescence (long-term).

Sea mussels are preyed upon by sea stars (particularly *Pisaster ochraceus*, but also *P. giganteus*, *Lepasterias hexactis* and *Picnopodia helianthoides*), predatory whelks (*Nucella* [=*Thias*] *canaliculata* and *N. emarginata*), crabs, fish, oystercatchers (*Haematopus bachmani*), black turnstones (*Arenaria melanocephala*), surfbirds (*Apriza virgata*), glaucous-winged gulls (*Larus glaucescens*), western gulls (*Larus occidentalis*) and sea otters (*Enhydra lutris*) (Hewatt 1937; Harger 1972; Marsh 1986; Paine 1976a; Shaw *et al*. 1988; Seed and Suchanek 1992)

Sea mussels are efficient filter feeders, selectively removing food particles from the water column. Organic debris provides a large component of the mussel diet, followed by dinoflagellates, diatoms, silicoflagellates and bacteria (Coe and Fox 1942, 1944; Fox and Coe 1943). Other foods include tintinnids, flagellates, ciliates and other protozoans, algal cells and fragments, algal spores, spermatozoa and ova, and inorganic particles such as sand and shell fragments. Sea mussels efficiently extract and concentrate toxins from harmful algal blooms and faecal coliform organisms, and thus present a human health risk if not monitored carefully[2].

Sea mussels are host to a number of parasites and disease agents (Bower and Figueras 1989; Bower 1992; Bower *et al*. 1994). None of these appear to present serious mortality risk. Sea mussels are not affected by haemic neoplasia, a significant cause of mortality of *M. trossulus* in B.C. (Bower 1989). Sea mussels are host to parasitic pea crabs (*Fabia* and *Pinnixia* spp.), which can decrease the general health and reproductive potential of mussels in the upper intertidal zone, where animals are already environmentally stressed (Anderson 1975).

Sea mussel beds are the habitat base for a large community of associated species (Suchanek 1979, 1981, 1985, 1992, 1994; Yamada and Peters 1988; Paine 1989; Seed and Suchanek 1992). On the outer Washington coast, local neighbourhood diversity ranged from approximately 20 species at high intertidal protected sites to approximately 140 species at low intertidal exposed sites. In total, over 300 species inhabit the interstices of established sea mussel beds. Seed and Suchanek (1992) described the three primary components of the mussel bed community as:

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[2] Interestingly, mussel poisoning was initially thought to be due to toxins produced by the mussel itself, linked to the production of gametes and the spawning cycle (Whedon 1936).

1) the physical matrix of living and dead mussel shells (ranging in complexity from a monolayer to several successive layers);
2) a layer of accumulated sediments, mussel faeces and pseudofaeces, organic debris and shell fragments (termed “gorp” by Suchanek [1979]); and
3) a taxonomically diverse arrangement of flora and fauna.

The physical complexity of mussel beds increase as they grow older. Successive layers of mussels are added, attaching to neighboring individuals, and progressively increasing spatial complexity and availability of microhabitats for use by associated species (Suchanek 1979; Seed and Suchanek 1992). Species richness increases with increasing mussel bed age and thickness, and decrease with increased intertidal elevation. Mussel beds also serve as a protective matrix which increases survival of small sea mussels, and thus increase recruitment rates.

Mussel beds regularly suffer episodes in which disturbance gaps are formed in the bed, usually through log battering, wave action, fouling, hummocking, or predation. Fouling by the algae *Fucus distichus*, *Laminaria* spp. and *Postelsia palmaeformis* and the barnacles *Semibalanus cariosus* and *Balanus nubilis* are greatly increased when mobile predators or grazers are at low densities (Witman and Suchanek 1984; Seed and Suchanek 1992). Hummocking, or raised mussel clumps secured to the surrounding bed only by byssal attachment to other mussels and not the substrate, may be the result of crowding and intraspecific pressure, or caused by the activities of porcellanid crabs (*Petrolisthes* spp.). Adjacent hummocks may be connected by tunnels, and are inhabited by vast numbers of crabs. They may also serve as initiation sites for disturbance gaps. Predation by sea stars and sea otters can cause disturbance gaps. Summer-formed gaps are smaller and form slower than winter-formed gaps, and winter gaps have a greater probability of increasing in size.

Mussel beds do recover from disturbance, and the rate of recovery is dependent on size of the gap, season in which the gap formed, intertidal elevation, angle of the substratum and intensity of larval recruitment (Seed and Suchanek 1992). Recovery of small gaps is rapid, through slumping or collapse of adjacent mussels. Larger gaps are dependent on some lateral movement of mussels into the gap, and thus require more time to recover. Extremely large gaps are recolonized by a succession of species, including diatoms, filamentous algae, barnacles and bay mussels. There follows a period in which the gap is dominated by bay mussels, balanomorph and gooseneck barnacles, and whelks. Sea mussels eventually colonize (ca. 20-26 months after disturbance in the mid intertidal), continue to expand, and eventually reclaim the disturbed area (ca. 60-80 months to decades after disturbance).

Typical studies of disturbed sea mussel beds show little recovery over 3-5 years (Hewatt 1935; Sousa 1984). Major disturbances in the mid intertidal range may require 8-35 years to recover (Paine and Levin 1981). Large areas of bare rock or upper intertidal disturbances require many years (est. 5-100+ years [Yamada and Peters 1988]) before sea mussel beds can be re-established (Dayton 1971; Seed and Suchanek 1992).

Sea Mussel Fisheries

Most fisheries that exploit *Mytilus* are based on bay mussels, *M. edulis*, *M. galloprovincialis*, and *M. trossulus*. Production from these fisheries is relatively low when compared to production from culture operations (Lutz 1980; Krause 1997). Commercial fisheries for sea mussels have occurred in Mexico (Baquiero C. 1997; Caceres-Martinez 1997), California (Shaw 1997), Oregon (Robinson 1997), and B.C. (Bourne 1997). Sea mussels have not been fished commercially in either Washington (Lindsay and Simons 1997) or Alaska (Foster 1997).

Mexico

Mussels have been used a subsistence food source in Mexico for centuries, and small scale fisheries continue to supply local markets in northern Baja California, accounting for less than 1% of total Mexican mollusc landings (Baquiero C. 1997; Caceres-Martinez 1997). Sea mussels, locally called “choros”, account for approximately 80% of the mussel production from the Pacific coast of Mexico (Baquiero C. 1997). Sea mussels were heavily exploited between 1967 and 1981, and attempts were made to develop culture operations to supply market demand while easing impacts on wild resources.

Mussels were removed *en mass* from mussel beds and sorted on shore. Market size mussels were bagged and transported, and small mussels returned to the fishing site. Mussels were then cleaned, cooked, boiled and packed for transport to a cannery.

Fisheries statistics are available from 1962 to 1993 (Caceres-Martinez 1997, his Fig. 5). Production between 1968 and 1981 was relatively high, averaging 430 t/yr, but was extremely variable. The fishery harvested all of the mussels in a known bed, and was sustained by discovery of new beds, which were subsequently depleted. Existing beds were quickly overexploited, and by the early 1970s fishers were turning to higher value species, such as abalone, lobster, tuna and sea urchins. Mussel beds recovered, and an attempt was made to redevelop a commercial fishery in 1991. This attempt failed, largely because product had to be transported over 1,200 km to a cannery in La Paz.

Attempts to collect sea mussel seed on spat collectors were not encouraging, but Mediterranean mussel (*M. galloprovincialis*) spat was collected. Subsequent culture efforts have been directed at this species, which has higher market value and acceptance (Caceres-Martinez 1997).

California

Bay and sea mussels have supported commercial fisheries in California in the past (Shaw 1997). The fishery for mussels declined after the 1920s, when the California State Board of Health closed most areas because of risk of PSP. A seasonal closure from May 1 to October 31 is still enforced for mussels for human consumption. Most or all of the annual landings are for bait. A limited sport fishery exists, open from November 1 to April 31, with a daily bag limit of 25 lb/person.

Oregon

The Oregon fishery for sea mussels began in 1979. The fishery was confined to 13 open permit areas on the outer coast of Oregon (Yamada and Peters 1988; Yamada and Dunham 1989). Landings peaked at nearly 30 t in 1989 (Table 1, Figure 1), and declined precipitously thereafter, until no significant landings were reported in 1996 or 1997 (J. McCrae, Oregon Department of Fish and Game (ODFG), pers. comm.). The landings are thought to be made up almost entirely by sea mussels, although some small amounts of bay mussels may be included (J. Johnson, ODFG, pers. comm.). Yamada and Peters (1988) indicated that the leveling off of catches in the late 1980s was due to depletion of mussel resources from the open areas.

The Oregon fishery was driven by a single buyer/distributor, who paid an unknown number of fishers to collect mussels for him. The mussels were primarily sold to restaurants and markets in Oregon. Although the reason for declining landings from 1989-1995 is not known, the recent lack of landings (1996-97) was due primarily to this buyer no longer participating in the fishery (J. Johnson, ODFG, S. Yamada, Oregon State Univ. (OSU), pers. comm.).

Yamada and Peters (1988) related an incident in which a 20 m stretch of shoreline was stripped of mussels by harvesters in central Oregon in 1979. The damage was still evident in 1988, and has only recently begun to support new sea mussel beds (S. Yamada, OSU, pers. comm.).

There are no assessment programs for sea mussels in Oregon. Management activities are also minimal; some areas have been closed after public complaints regarding harvesting impacts on local mussel beds (J. Johnson, ODFG, pers. comm.). A limited sport fishery exists, with a daily limit of 72 mussels/person (Robinson 1997).

British Columbia

Current harvest of sea mussels in British Columbia are limited to recreational fishing and collection of animals for biotoxin monitoring programs in support of other bivalve harvests.

The recreational fishery is managed under a daily bag limit of 25 mussels (total possession limit is 50 mussels) in the South Coast, with a reduced limit of 12 mussels/person/day in Pacific Rim National Park on the west coast of Vancouver Island. The North Coast is closed to mussel harvests, due to the lack of biotoxin monitoring programs. Recreational harvests are by hand-picking only.

Bourne (1997) indicated that some minor attempts at commercial fisheries for both bay and/or sea mussels had occurred, and expressed doubt that fisheries for either species could be established because of harvesting economics and poor quality.

Mussel landings are available, although the mussels are not separated to species (*i.e.*, landings may represent either sea or bay mussels, or a combination of species) from 1983-1990, after which mussel licences were no longer issued. Landings during this period averaged 0.9 t per year, with a maximum of 2.5 t in 1988. Recent harvests for biotoxin monitoring programs averaged 2 t per year between 1996-1998, and did not exceed 3 t in any year (K. Schallie, CFIA, pers. comm.).

Stock Assessment Information Requirements

The U.S. National Research Council provided a checklist of items that should be included and/or considered in a stock assessment (NRC 1998). This framework is used to evaluate existing data, and to propose specific studies or experimental fisheries to obtain missing assessment information for the proposed sea mussel fishery.

Stock Definition

Sea mussels, like many infaunal or epifaunal mollusc populations, are a classic example of a metapopulation. A metapopulation is a system of local populations that interact via individuals moving among populations, *i.e.*, are connected by dispersing individuals (Hanski and Gilpin 1991). Because adult mussels are essentially sessile, the interaction is accomplished via settlement of pelagic larvae into mussel beds other than the one from which they were produced. In metapopulation jargon, a mussel bed is a habitat patch, and the mussels making up the bed are a local population.

Given that adult populations are virtually sessile, and that mussel beds are easily defined (and entirely accessible to both surveys and fisheries), spatially structured assessment and management approaches are possible. Similar to geoduck (*Panopea abrupta*) populations in B.C., individual beds, while not representing genetically distinct stock units, are likely the appropriate management unit for the fishery, especially during exploratory or experimental harvests.

Exploratory or experimental harvests are required to assess stock responses to harvest. Traditionally, such research has concentrated on the effects of harvest on the target species alone. Given that mussel beds are not just aggregations of mussels, but rich and complex successional communities, assessments should explore the effects of harvest on community structure and biodiversity (see discussion under Ecological Data, below).

The degree of spatial resolution possible for a full-scale commercial fishery will likely be economically determined. The fine-scale management in the geoduck fishery is made possible by the high unit value of the product. It is unlikely that sea mussels will command a similar price.

Estimates of Removals – Catch and Habitat Monitoring

Four methods of documenting catch from B.C. fisheries are commonly used: sales slips, harvest logbooks, dockside or port validators and fishery observers.

Sales slips provide minimal information and resolution, usually only date of sale, fishing method, vessel/fisher identification (fisher's name, vessel CFV number, etc.), species caught, catch weights, statistical area and/or subarea where the catch was made, and the buyer. Sales slips can also be somewhat ambiguous if product is stored from several fishing operations, and sold later.

Harvest logbooks can require greater detail for each fishing operation, including geographic references (specific fishing locations, lat/long coordinates, etc.), catch weight or number caught, detailed information on gear type or fishing method, effort expended during the fishing operation, and other remarks or comments.

Dockside validators or port monitors, in addition to verifying that catches on sales slips and logbooks have been filled out correctly, can subsample catches to provide detailed species composition or other biological information. They cannot, however, verify whether reported fishing locations and/or effort are accurate. This is only possible with an on-grounds fishery observer.

Sales slips and logbooks are a bare minimum acceptable reporting structure for a sea mussel fishery. The importance of verifying exact catch locations (individual beds), the need to ensure that only responsible harvesting practices have been used, and the requirement for monitoring fishing locations for additional incidental (environmentally induced) impacts of harvesting require an on-grounds observer/fishery coordinator.

Abundance Estimates - Potential Survey Designs

Several B.C. invertebrate fisheries involve selection of individual animals by hand (sometimes with tools or implements to aid in collecting them), either in the intertidal zone or by divers, and in which the animals are distributed into definable aggregations (*e.g.*, intertidal clams, primarily *Venerupis philippinarum*, *Protothaca staminea*, *Siliqua patula* and *Saxidomus gigantea*; geoducks; sea urchins, *Strongylocentrotus droebachiensis* and *S. franciscanus*; and sea cucumbers, *Parastichopus californiensis*). The most commonly used methods to estimate biomass in assessments of these fisheries are a representative estimate of mean density expanded over some index of total habitat. Indices of habitat size used include:

1) defined total area, *e.g.*, Gillespie *et al*. (1998), Jones *et al*. (1998) and Kronlund *et al*. (1998) for intertidal clams;
2) estimated bed size, *e.g.*, Campbell *et al*. (1998) and Hand *et al*. (1998) for geoducks;
3) depth range limits, *e.g.*, Waddell *et al*. (1997) and Jamieson and Schwarz (1998) for green and red sea urchins, respectively; or
4) linear measure of shoreline, *e.g.*, Boutillier *et al*. (1998) for sea cucumbers.

Mussel beds are highly visible, clearly defined aggregations, often the dominant feature of the rocky intertidal zone (Suchanek 1992). Delineation and measurement of individual mussel beds is easily accomplished, and thus, all that is required is to estimate the mean density of mussels in the bed. This level of resolution is particularly important during experimental harvests, where the objective is to determine the response of the bed to harvest practices.

The first step in determining the extent and biomass of mussel populations in an area is a broad-brush distributional survey. Individual mussel beds are located, their centers georeferenced using a differential global positioning unit (DGPS), and its dimensions and total area determined. Determination of bed area is easily accomplished with a 100 m measuring tape or surveyor's chain. The length of the bed is measured (parallel to the water line) and width measurements are taken incrementally along the length axis (*e.g.*, every 5 m for small beds, every 10 m for large beds). These measurements can be used to estimate total area, either by hand using trigonometric relationships, or by using a geographic information system (GIS).

Robles (1987) and Robles *et al*. (1995) used a stratified random quadrat array to sample mussel beds in southern California and Barkley Sound, B.C. Permanent transects (10 m in length in California, 1 m in length in B.C.) were arranged parallel to the water line at 30 cm intervals perpendicular to the water line. In B.C., sets of transects were added adjacent to each other until the mussel bed was encompassed by the sampling frame. In both instances, randomly selected quadrats (5 per transect in California, 2-3 per transect in B.C.) were sampled on each transect. Quadrat size was 230 cm^2 in California, and 400 cm^2 in B.C. This protocol was designed to monitor changes in distribution and species composition over time, not to produce absolute estimates of abundance. There are no unbiased estimators in classical probability statistics which would allow calculation of confidence intervals for an estimate produced using systematic selection in other than the final stage of sampling (Kronlund *et al*. 1998).

Survey protocols for intertidal clams (Gillespie *et al*. 1998; Kronlund *et al*. 1998) can be easily applied to sea mussel surveys. Sampling intensity (the number of quadrats required for a given area) and quadrat size will need to be determined for sea mussel surveys. Recommended quadrat size for Manila and littleneck clams is 0.25 m^2 (50 x 50 cm), and recommended sampling intensity is 30 quadrats/ha. Paine (1989) recommended that harvesting be limited to 100 cm^2 areas, to allow quick recovery of bed integrity. Larger quadrats, up to 400 cm^2 (Robles *et al*. 1995), have been used by other authors.

Sample quadrats are then selected using a two-stage survey design. In the first stage, distances are selected along the length axis of the bed. If quadrat size was 10 x 10 cm and the length axis was 100 m, then there are 1,000 possible quadrats available for selection along the length axis. A quadrat position is selected at random between 0 and 999, 432 for this example. This quadrat position is then converted to real distance by dividing by the quadrat size (0.1 m), and the first selected distance is thus 43.2 m.

Any additional information on bed structure, *e.g.*, which portions of the bed are composed of only a single layer of mussels and which portions have multiple layers, can be used to partition the bed into strata, with the potential benefit of reduced variances and smaller confidence intervals associated with the resulting estimates (Kronlund *et al*. 1998).

At each selected distance, which now represents a strip cluster of quadrats (*fide* Kronlund *et al*. 1998), the width of the bed is measured. In the second stage, three quadrats are placed systematically along the strip cluster from a randomly selected starting point. For example, if quadrat area was 10 x 10 cm and the bed was 10 m wide at the selected distance, then there are 100 possible quadrats available for selection. The next largest sample frame that can be evenly divisible by three (the number of quadrats to be selected) is 102, representing three 34-quadrat clusters arranged end-to-end. A random starting point is selected between 0 and 33, 17 for this example. The remaining quadrat locations are determined systematically (by adding 34 to the initial starting point) at 51 and 85 quadrat positions. These positions are then converted to real distances by dividing by the quadrat size (0.1 m), resulting in real distance locations of 1.7 m, 5.1 m and 8.5 m. The randomization process is repeated independently for each first stage selection.

The systematic placement of the quadrats along the selected strip cluster ensures even sampling over the strong gradient in biological parameters (recruitment, growth and condition index) that is apparent from high to low intertidal portions of local mussel populations.

A quadrat frame is used to select animals which are to be sampled; animals which have at least half of their body inside the quadrat frame are included. All sampled animals are bagged, labeled and retained for detailed processing.

Data required for biomass and abundance estimates are total count and total weight per quadrat. These data may be taken by size category, to assess biomass trends in sublegal, legal and/or supralegal portions of the local population in successive surveys.

Mean density (expressed as either biomass or abundance) and their associated variances can then be estimated using either the two-stage or stratified two-stage estimators provided by Kronlund *et al*. (1998). Mean estimates are then expanded by bed area to give estimates of total biomass or total abundance. The variances are expanded by the square of bed area, and can then be used to calculate standard 95% confidence intervals.

Biological Information

Data required for determining biological characteristics of the local population include individual length and weight, individual age, and possibly reproductive maturity and condition index. Quadrat samples should be selected at random from all available samples and all mussels in each selected quadrat sampled to ensure unbiased estimates representative of the entire local population. The systematic arrangement of high, middle and lower intertidal samples in the previous protocol allows a stratified approach to selecting samples for biological information and interpretation of the results. Individual length and weight are easily measured from survey and commercial catch samples. Other biological parameters are more difficult to obtain.

Age

Age determination for bivalves generally follows one or more of the following methods:

1) size frequency analyses;
2) interpretation of growth checks in the shell; or
3) experimental tagging studies.

Growth rates within local mussel populations are usually so variable that size frequency analyses cannot be used to discriminate year classes (Jamieson *et al*. 1975). Seed (1976) felt that modal analyses are generally possible for species with a relatively restricted recruitment period and with fairly uniform growth rates within year classes. The extended reproductive period of *M. californianus* may make use of modal analyses difficult, and differences in growth rate between animals in the same year class situated at different tidal heights or aggregated at different densities would need to be considered when selecting samples for modal analyses.

Interpretation of growth checks on shell surfaces is difficult due to the number of types of events that can result in check formation (Coe and Fox 1942), including reproductive processes, temperature, food supply, storms, exposure to air during low tides, and stresses from disturbance or handling.

Ages for other mussel species have been determined by examining shell sections and interpreting growth lines in the inner and middle nacreous layers (*e.g.*, Anwar *et al*. 1990 for *Modiolus modiolus*; Lutz 1976, Richardson 1989 and Richardson *et al*. 1990 for *Mytilus edulis*). This technique should be explored for sea mussels in B.C. It would provide quick, though relatively expensive, information on age, which is required for determination of population structure, growth, recruitment and mortality rates.

Growth

In the absence of reliable ages, size specific growth rates can be determined through tagging studies (Yamada and Dunham 1989), or experimental placement of selected size classes into enclosures (*e.g.*, Harger 1970). This avenue of investigation should be pursued, both as insurance should direct ageing techniques prove untenable, or as a parallel investigation to provide verification of ages determined through direct methods.

Growth rates are extremely valuable for determination of age at maturity and compensatory capacity for species managed with size limits (*e.g.*, Gillespie *et al*. 1998). The compensatory capacity (*i.e.*, the ability to recover from disturbance) of mussel beds is assumed to be relatively low, as the literature contains numerous references to prolonged recovery periods, on the order of decades, from natural and human-induced impacts to bed integrity (Suchanek 1981, 1992; Yamada and Peters 1988; Yamada and Dunham 1989; Paine 1989). To my knowledge, compensatory processes, as they relate to selective removal of certain size classes from mussel beds, has not been explored.

Sex and Reproductive Maturity

The sex of sea mussels cannot be determined without histological preparations or examination of extruded gametes: there are no visible dimorphisms (Seed 1976). When explicitly examined, sex ratios have generally proven to be approximately equal (Seed and Suchanek 1992).

Reproductive maturity can be determined histologically, but some caution is required. Although gonad differentiation is detectable in *M. californianus* at 25-30 mm, the smallest sea mussel that Young (1945) was able to induce to spawn was 55 mm, and Coe and Fox (1942) estimated size at first spawning to be 70 mm. Suchanek (1981) estimated size and age of first reproduction at 35-40 mm using gonadal weights. He cautioned, however, that gonadal weights may be misleading as storage products (*e.g.*, glycogen) are also present in gonad and mantle tissue, and thus may bias results.

Determination of size at first spawning might be most readily accomplished by using the histological techniques and reproductive staging described by Bartlett (1972) to examine a range of sizes of mussels throughout the year. The information might be corroborated by attempting to induce spawning (probably through the use of hormonal cues from macerated gonads) in size selected samples of mussels.

Condition Index

Condition index is often used as an index of general health and reproductive condition of bivalve molluscs. Condition index is generally measured as the ratio:

$$I_C = \frac{Wt_{SBD}}{SV} x100 \tag{1}$$

where Wt_{SBD} = dried weight of the soft body parts, and SV = shell volume. Shell volume may be measured by filling the empty shell with either water or sand, and converting the weight of the filling substance to volume by dividing by its density (Baird 1957; Quayle 1969; Anderson 1975; Davenport and Chen 1987).

Anderson (1975) also used other indices to measure relative impact of parasitic pea crabs (*Fabia subquadrata*) on sea mussels. His "body component index" was calculated as:

$$I_{BC} = \frac{Wt_c}{Wt_{SB}} x100 \tag{2}$$

where Wt_c = the wet weight of the body component considered (gonads, viscera, mantle, gills, etc.) and Wt_{SB} = the wet weight of all of the soft body parts in total. He also described a "soft body index":

$$I_{SB} = \frac{Wt_{SB}}{Wt_{Total}} x100 \tag{3}$$

where Wt_{Total} = the wet weight of the intact animal.

Condition of the mussels may have bearing on their marketability. Anecdotal information indicates that there is a period of the year when sea mussels are visibly spent (A. Sutton, VISCO, pers. comm.). Yamada and Dunham (1989) reported low condition index values in January 1987 and January and February 1988, and suggested that there may be a period in the winter when sea mussels are of marginal marketability.

Sampling Catch

The most convenient method of reporting catch (and tracking TACs, if they are used) will be landed weights. Representative subsamples of each landing should be counted and weighed to determine average weights. These can be used to convert landed weights to number of individuals landed.

Concerns over whether catches are representative of local populations must be considered before using fishery-dependent samples for monitoring biological parameters. From the literature, it is apparent that intertidal elevation greatly affects important parameters such as condition index and growth. Intertidal elevation generally cannot be accounted for when subsampling commercial catches, and thus, commercial catch samples are of limited utility. The use of size limits to regulate the fishery enforces size selection on the catch, and biological characteristics estimated solely from commercial catches will likely be biased and unrepresentative of population parameters.

Mortality

The three most common methods for estimating natural mortality (Vetter 1988) involve:

1) analyses of catch data, either from commercial catches or surveys, including mark-recapture studies;
2) correlations of M with other life history parameters; or
3) estimation of deaths due to predation.

For samples of unmarked animals, ages are either determined directly, or size-frequency distributions from samples of unmarked animals are converted to age-frequency distributions based on previously determined relationships between age and either length or weight (growth curves). The resulting age-frequency distributions are then examined through catch curve analysis (Ricker 1975).

The basic assumptions of analyses differ depending on whether the catch curves represent multiple age classes from a single sample (horizontal curves) or repeated sampling of an identifiable group over a protracted period of time (longitudinal curves). In the first case, assumptions are that recruitment has been constant for all age classes and that mortality rates have been the same for all animals achieving that age. In the second case, assumptions are that groups are adequately identifiable, all groups are closed to migration or that migration is proportional to the age distribution, samples are representative of the true composition of the groups in the population, rates of mortality are relatively constant for each group over time, and compensatory relationships between population size or fishing mortality and natural mortality do not exist (Vetter 1988).

The use of catch curve analyses for sea mussels in B.C. requires information on age, or on growth rates to assign age classes to length-frequency data (however, see discussion of modal analyses in the Age section above). The use of mark-recapture methods to estimate mortality overcomes many of these difficulties, particularly with sessile adult mussels, but requires assumptions regarding mark-induced mortality, tag loss, or (if a commercial fishery is used to recover tags) under-reporting or incorrect reporting of recaptures.

The simplest, though perhaps expensive and time-consuming, method for using catch curves to estimate mortality might be a size-and habitat-structured tagging program in an unfished study area. This would entail recovering and releasing tagged individuals over several successive time periods, entailing years of research.

The second approach is through examining correlations between *M* and other life history traits. Vetter (1988) outlines several studies which estimate natural mortality rates from maximum age or size, age or size at maturity, parameters of growth models, or measures of physiological indices or rates.

The most familiar of these relationships is that of Hoenig (1983) which regresses known *M*s from various mollusc species to their maximum age:

$$\ln(M) = 1.23 - 0.832(\ln(T_{\max})) \tag{4}$$

where T_{max} is maximum age. Using this relationship and a maximum age of 50-100 years for sea mussels, estimated *M* ranges between 0.074 and 0.132 (Table 2). Obviously, more dependable estimates of *M* require extensive sampling of larger (and thus, presumably older) mussels and development of reliable age determination methods to determine longevity in B.C.

The third method requires simultaneous cohort analyses of a multispecies assemblage incorporating major predators and alternative prey for the community in question. The data requirements are too onerous for the method to be considered for sea mussels at the present time.

Recruitment

Recruitment can be assessed through examination of age structure, whether the structure is compiled directly from age determinations, or inferred from length frequency distributions and other growth information (Cerrato 1980). In general, if recruitment and mortality are constant, then the resulting age structure is a smoothly declining curve from settlement to maximum age. Departures from this pattern could be interpreted as varied levels of recruitment. For example, if the frequency of a given size class is less than would be expected, either initial recruitment of that cohort was unusually low, or mortality rates have been higher in that cohort than in adjacent ones.

Recruitment is a function of initial abundance and mortality rates, and the relative contribution of the two factors will be difficult to separate. There are a number of references in the literature describing compensatory mortality by starfish and predatory gastropods on large settling cohorts of mussels, which tend to keep recruitment rates at fairly consistent low levels (Dayton 1971; Harger 1972; Paine 1966,1974).

Environmental Data

Given the paucity of information on population size, distribution and characteristics of sea mussels in B.C., there is insufficient information to assess the effects of past environmental changes on population trends. It is important, however, that control populations be assessed on a regular basis if population trends from fished beds are to be attributed to either fishing pressure or environmental change.

Ecological Data

FAO precautionary approaches to fisheries require assessment of impacts of harvest practices on associated species (FAO 1996). Harvest practices detrimental to mussel populations can cause local reduction or extirpation of many species (and, in fact, induce community collapse due to habitat loss). Viewed at the ecosystem level, mussel harvests are habitat alterations.

Some monitoring of ecosystem characteristics (total diversity or species richness) should be conducted as part of the assessment of harvested beds. It is clear from the literature that serious impacts on mussel bed integrity (clearcutting of patches to bare rock) result in loss of biodiversity, it is unclear what effect limited harvest practices, such as removal of overlying layers of mussels leaving only a single layer over bare rock, might have. The literature suggests that species richness (community diversity) increases as bed thickness increases; however, it is unclear whether this is a function of bed thickness alone, or of bed age, which is confounded with bed thickness.

Assessment Models

Choices available for assessment models for sea mussels are currently extremely limited, due to the lack of information on age structure, growth, longevity, natural mortality and fishery performance.

Analyses of Abundance Trends

Monitoring of abundance trends over time was the second most common method of stock assessment (following age-structured analyses) used for U.S. fisheries in 1995 (NRC 1998). These trends included CPUE or fishery-independent surveys. The use of these techniques is implicit in closely monitoring individual mussel beds under experimental harvests.

Surplus Production Models

Surplus production models can be used to develop biological reference points for fisheries management with only modest data requirements. The Gulland model calculates maximum sustainable yield as:

$$MSY = XMB_0 \tag{5}$$

where M is the estimated natural mortality rate, B_0 is the unexploited biomass, and X is a scaling factor, with suggested values between 0.4-0.5 (Gulland 1971; Caddy 1986). Garcia *et al*. (1989) considered these scaling factors to be too liberal for data-limited fisheries development, and Boutillier *et al*. (1998) opted to use half of the lower scaling factor for B.C. sea cucumber fisheries.

Other Potential Models

Walters (1998) suggests that an optimal fishing mortality might be 2/3M, which would result in harvest rates between 4.8-8.5%. However, given the uncertainty in the estimate of M, the possibility of extreme longevity, and the simplicity of the production model, this is not considered a conservative option.

Other assessment models recommended by either the National Research Council (NRC 1998) or Hilborn and Walters (1992) have minimum data requirements which cannot be met at this time for sea mussels. Biomass dynamic models require time series of abundance and fishery-dependent data which are not available. Other approaches (*e.g.*, aggregate matrix, integrated or fully-integrated models) require age or size structure, recruitment or biomass indices, and/or fishery-dependent data.

Potential Management Tools

A number of management tactics are used to control fisheries for invertebrates, including limiting catch by size, sex or season, area closures, total allowable catches (TACs), or using biologically relevant management targets or thresholds. Some options relevant to the proposed sea mussel fishery are discussed below.

Size Restrictions

In B.C., size limits are used in several commercial invertebrate fisheries, including intertidal clams, red and green sea urchins, pink and spiny scallops (*Chlamys rubida* and *C. hastata*), prawn (*Pandalus platyceros*) and shrimp (*Pandalus* and *Pandalopsis* spp.) by trap, and crab (*Cancer magister* and *C. productus*) by trap (Harbo and Hobbs 1997). Minimum size limits are used to prevent harvest of immature animals.

Minimum size limits for Manila, littleneck, butter and razor clams are based on size at first maturity (Quayle and Bourne 1972). The best information currently available indicates that sea mussels do not spawn until 70 mm in length (Coe and Fox 1942). Thus, 70 mm is a logical minimum size limit, though there are reasons why this may not be particularly conservative. Bivalves have a tendency towards protandry (N. Bourne, DFO, pers. comm.), and thus sublegal animals may be predominantly male. Bivalves may mature at relatively small sizes, but may not spawn during the first season after attaining maturity (N. Bourne, pers. comm.). Whether this is the case for sea mussels is not known. Additionally, because information from the literature is from the southern extent of the species range, managers may wish to cautious, and increase the minimum size limit until information is available on size at first functional spawning in B.C.

If market preference in B.C. is similar to that in Oregon, then the marketable mussels would be between 40 and 70 mm (S. Yamada, OSU, pers. comm.). This would require that the fishery be conducted on immature animals, and may be a contributing factor to the inability of mussel beds in Oregon to sustain harvests.

Maximum size limits are used to protect mature animals based on their reproductive potential. Fecundity increases with size in *M. californianus* (Shaw *et al*. 1988), and mortality is thought to decrease to extremely low levels at larger sizes (Paine 1976a). Therefore, animals that are too large for market acceptance, and which still represent great reproductive potential, could be protected with a maximum size limit. Paine's data (1976a, his Fig. 4) suggests that starfish predation decreases considerably above approximately 100 mm TL, therefore, this might be considered as a possible maximum size limit. These animals are more valuable attached to the rocks (Paine 1989; Suchanek 1992) than they would be if retained and processed as bait (Krause 1997). There would be additional benefits in conserving the mussel bed matrix, both as a preferred settlement substrate (increased recruitment), and as habitat for numerous species which comprise the mussel bed community (conservation of biodiversity).

A maximum size limit might initially be set based on market preference, but initial assessments of size frequencies from mussel beds proposed for harvest should be examined to determine whether a significant portion of the local population would be conserved.

Very little information is currently available to explore the implications of these theoretical size limits. A single quadrat sample was taken at Cardigan Rocks, B.C., on October 23, 1998. Quadrat area was approximately 0.09 m^2 (25 x 35 cm), and contained 113 mussels. Size ranged from 6-125 mm (Figure 2) with too few animals sampled to develop meaningful length modes. If 70 mm were accepted as a minimum size limit, and if this sample was representative of the entire bed, then 51.3% of the available stock would be excluded from harvest. Likewise, if 100 mm were accepted as the maximum size limit, another 16.8% of the local population would be excluded from harvest. Thus, this combination of size limits would protect 68.1% of the population (by number), leaving a third of the population available for harvest. This potential harvest rate is considerably greater than the approximately 1-2% suggested from limited production modeling.

This example is included because it is the only data currently available on size distribution of sea mussel populations in the Port Hardy area. The sampling site at Cardigan Rocks was selected only because it was one of the closest mussel beds to Port Hardy. Given that the maximum size from the sample was less than half the known maximum size for the species, this population is likely not representative of all local populations in B.C. Other local populations with faster growth rates and increased maximum size could have a larger broodstock component protected by the maximum size limit. These populations could also be more productive, as animals would grow into (and through) legal size more rapidly.

Rotational Harvests

If the fishery is managed by a combination of size limits alone, and exploitation rates are high within the legal size range, then recovery periods will be required to allow mussels to grow through legal size and into the refuge provided by the maximum size limit. The period of rotation of harvest will be determined by estimated growth rates and the size limits chosen to manage the fishery.

Harger (1970) estimated growth of sea mussels in California. His graphs indicate that, on average, a size of 70 mm would require 2-3 years growth in the lower intertidal and 7-8 years in the upper intertidal. A size of 100 mm would require approximately 5 years in the lower intertidal and was not achieved in the upper intertidal. This implies a rotational harvest cycle of 3-6 years, if some animals are to be allowed to grow into the upper size refuge.

Responsible Harvesting Practices

Preventing improper harvesting practices, *i.e.*, practices which either directly or indirectly result in incidental mortality or loss of mussel bed area, is of paramount importance if sea mussels are to be harvested in a sustainable manner. Loss of animals due to indiscriminant harvest and discarding renders management tactics such as size limits or TACs ineffective in ensuring conservation. Because mussel beds are the dominant feature of the rocky intertidal zone, harvest practices that result in loss of bed area will be immediately visible, and negative public reaction to unscrupulous harvesting in Oregon resulted in area closures and reluctance to expand the fishery (Yamada and Peters 1988).

The most responsible means of harvesting sea mussels is to selectively remove animals of market (or legal) size, leaving the rest of the bed matrix intact. Sea mussels are quick to lay down new byssal threads: animals placed in a bucket after weighing and measuring had already attached to the bucket surface in less than 30 minutes (G. Gillespie, personal observation). Animals that are accidentally dislodged during harvest can be gently pushed back into the bed matrix, and will re-attach (S. Yamada, OSU, pers. comm.).

Habitat Protection – Ban Clearcutting

Yamada and Peters (1988) and Paine (1989) both expressed strong concern over the consequences of indiscriminant large-scale removal of mussels that result in large clearcut patches. Clearcuts do not recover through movement of adults from distant areas or direct recruitment of juveniles, but rather must pass through a long successional sequence of species until the mussel bed is finally restored (Hewatt 1935; Dayton 1971; Suchanek 1981; Paine and Levin 1981; Seed and Suchanek 1992). There is a further lag time in re-establishing the mussel bed community after initial recolonization by *M. californianus* (Seed and Suchanek 1992). In light of the impact of producing large areas denuded of mussels, both advocated leaving at least a single layer of mussels on the substrate after harvest.

Other Harvest Practice Considerations

Paine (1989) recommended that mussel harvests be confined to very small, spatially separated areas. When patches are formed in mussel beds, whether through natural causes or directed removals, recovery of bed integrity is dependent on the availability of adjacent mussels (Paine 1989). Small patches (<100 cm^2) recovered relatively quickly due to adjacent mussels leaning or being forced in to the gap. Recovery of moderate sized patches (3,500 cm^2 or less) required for 1-3 years. Larger patches recover very slowly, and remain recognizable for years after their formation.

Paine (1989) also recommended that harvests be confined to the lower two-thirds of the mussel bed. Levels of recruitment, growth and mortality rates all vary with tidal height. Test strips cut vertically through mussel beds in Washington State showed varying amounts of recovery at their upper extremes (Paine 1989). One strip at Mukkaw Bay showed essentially no recovery for 24 years. A fishery which selectively harvests mussels from the upper intertidal is impacting the portion of the stock that is least able to recover from removals. In general, the highest tidal elevations will be accessible first (as the tide falls) and last (as the tide rises), and therefore will likely receive more attention from harvesters.

Area Closures

Area closures are designed to provide refuge for exploited species and/or protection of habitats required by exploited species. They are strongly recommended during the development of new fisheries, particularly if the results of proposed management are very uncertain (FAO 1996). Area closures are most effective when the conservation target remains within the closed area. Because adult mussels are essentially sessile, area closures can be an effective tool for mussel bed community conservation.

Much of the area under consideration for experimental harvests near Port Hardy is protected as Provincial Park (Cape Scott and God's Pocket Provincial Parks), ecological reserve (Duke of Edinburgh Ecological Reserve), ICZM Primary Study Area (Walker and Deserter's Group), or as First Nations reserves (Hope Island, and portions of Nigei and Balaklava Islands). Other areas are focal points of conservation concern from local dive operations (Bate Passage), who are seeking some form of protection. The habitat favoured by sea mussels is not attractive to divers, and thus, an experimental harvest area is not likely to conflict with recreational dive interests. The northwestern shore of Nigei Island has large mussel beds (E. Casefield, VISCO, pers. comm.), is relatively close to Port Hardy, and is distinct from the protected areas listed above. This shoreline holds the most promise for experimental harvests in Statistical Area 12.

Seasonal Closures

The objectives of seasonal closures might include protecting stocks during reproductive periods or other critical life stages, limiting fishing effort, maximizing product quality, or safety considerations. Because reproduction and recruitment in sea mussels are not strongly seasonal, this is not strong justification for a seasonal closure. Direct means of limiting catch (size limits, TACs) are more effective than effort limits in ensuring conservation goals.

However, other considerations might inspire managers to consider a winter closure. Given available information on seasonal variation in condition index, and thus marketability of sea mussels (Yamada and Dunham 1989; A. Sutton, VISCO, pers. comm.), a seasonal closure may be considered to avoid wasting production or affecting market perception of product quality. Paine (1989) has suggested that harvesting activities be confined to the late spring and summer months. Timing the fishery in this way allows a recovery period for mussel beds to repair the effects of harvest, and perhaps minimizes the risk of large scale damage and incidental mortality due to wave scouring during winter storms. In addition, the combination of night-time low tides and inclement weather greatly increases the risk of mishap, if fishing is conducted in the winter months.

Unfortunately, a summer fishing season coincides with the highest probability of closure due to PSP outbreaks on the west coast of Vancouver Island (Harbo *et al*. 1997a) and in Areas 11 and 12 (Harbo *et al*. 1997b).

Total Allowable Catches

If mussel fisheries are managed at the bed level, then individual TACs can be assigned in a manner similar to that used in the geoduck fishery (Hand *et al*. 1998) and in the depuration fishery for intertidal clams.

Estimation of unexploited biomass is relatively simple in this case, as each bed can be assessed prior to harvest. For a larger scale commercial fishery, where assessing each bed annually is impractical, representative beds (selected at random from the known beds in an area) could be assessed, and an average density for beds in the geographic area developed. This average density (or the lower 95% confidence limit of the estimate, if managers wished to be conservative) could then be expanded by the measured bed area to give preliminary estimates of biomass for each bed. Preliminary densities could be ground-truthed through limited sampling by the on-site observer.

Using 0.2 as a scaling factor (*fide* Garcia *et al*. 1989) and the estimates of M from Hoenig's equation for 50 and 100 year lifespan, the target harvest rate would be between 1.5-2.6% of the unexploited biomass (Table 2).

Reference Points – Thresholds and Targets

Biological reference points (BRPs) are calculated entities which describe aspects of stock status (*e.g.*, spawner indices, biomass levels, etc.), but are also often fishing mortality rates (NRC 1998). They can be used either as targets to define optimal fishing, or as thresholds to define overharvest, which then trigger remedial management actions (FAO 1996). Target BRPs are always more conservative than threshold BRPs, and some separation between them is advised to avoid triggering management responses on minor overages of the target.

The harvest rate suggested from limited production modeling (1.5-2.6% of unfished biomass) might be an appropriate target reference point. A critical threshold limit might be biomass based. A biomass based threshold of 50% of unfished biomass is used in the B.C. geoduck fishery (Hand *et al*. 1998). Geoducks are also sessile bivalves, with similar life history parameters to those presently understood for sea mussels. Thus, this might be considered as a preliminary threshold for sea mussel fisheries. If the estimated biomass in any bed falls below 50% of the estimated initial biomass, management actions, including fishery closure, could be invoked.

Discussion

Among the undesirable or unacceptable outcomes listed in the FAO Technical Guidelines for Responsible Fisheries are overexploitation of resources, loss of biodiversity and major physical disturbances to sensitive biotopes (FAO 1996). Mussel beds form the structural basis for complex communities, supporting a remarkably diverse fauna for a temperate ecosystem. Sea mussels are a relatively long-lived species, with low recruitment rates and numerous age classes represented in the standing stock. These life history characteristics require that harvest rates be very low, if the harvest is to be sustainable.

Although little quantitative information is available on life history and production parameters of sea mussels, particularly in B.C., enough qualitative information exists for several authors to have expressed concerns regarding commercial harvest of the species.

Hewatt (1935) studied succession in a sea mussel bed in Monterey Bay, California, over 2.5 years. He listed over 20 taxa of invertebrates (not including unidentified amphipods) from a single square yard, and documented limited recolonization of the area after it had been cleared. Although recovery was relatively rapid, because his experimental patch was surrounded by sea mussels, he was still inspired to comment on "the caution which should be exercised in the commercial exploitation of the *Mytilus* beds."

Yamada and Peters (1988) related an incident demonstrating the impact and consequences of irresponsible harvesting practices (see Sea Mussel Fisheries, above), and expressed the opinion that production from the fishery in Oregon had leveled off due to stock depletion problems. They advocated leaving at least a single layer of mussels, stating that "for the continuation of the commercial *Mytilus californianus* harvest, it is paramount to leave existing mussel beds intact".

Paine (1989) discussed the consequences of fishery development and suggested methods for environmentally responsible regulation of a fishery for sea mussels. His concern was that harvests of natural populations of sea mussels would produce environmental pattern, in the same way that clear-cutting forests does. The effects would be most dramatic when patches of mussels are removed from the upper intertidal, as recovery of bed integrity is considerably slower there than at lower intertidal elevations. There was a strong seasonal component to recovery, as well. Winter patches tended to become larger and take longer for recovery. He also suggested that mussel production might be increased by removal of starfish from the lower margin of mussel beds, and that selective removal of upper layers (where more than one layer of mussels was present) could increase the growth rate of the monolayer of mussels left behind. Both of these last suggestions may have ecosystem implications: removal of a predator in the first case; and alteration of the spatial matrix of the mussel bed in the second. Although increased production from remaining mussels might be realized, community structure and biodiversity are correlated with tidal height, the age of the mussel bed and the thickness of the mussel bed. Increased production from the remaining mussels may be a poor trade-off, if community structure and diversity are greatly impacted.

Paine (1989) argued for the protection of sea mussel stocks because "natural mussel beds are important reservoirs of biological diversity, harboring a minimum of 300 resident species...although these associates can and do exist elsewhere, the bed appears to be their primary habitat…destruction or even substantial modification of the bed will, inadvertently, have a negative influence on a host of associated species". He further argued that "the inexorable consequence of harvesting – even if biologically proper and stringently regulated – will be a substantial disappearance of mussel beds, a decline of habitat quality for the associated species, and the initiation of conspicuous changes in shoreline appearance. The net result will be socially and ecologically unacceptable lengths of time for recovery." Although he outlined environmentally acceptable harvest practices, he felt that these "would either be unenforceable or would require almost saintly restraint on the part of the harvester…in the wave-swept, potentially hazardous environments favored by sea mussels, most of the suggested practices are unrealistic."

Suchanek (1992) briefly described the structure and dynamics of sea mussel communities, with the recommendation that "because of the extreme 'instability' of some high intertidal components of this community in the face of disturbance agents that disrupt the biological mussel matrix, special care must be taken to protect this uniquely diverse community from human-induced impacts". Suchanek (1994) advised against inducing further impacts on mussel bed communities. Although some of the ecological linkages in these communities are known, particularly keystone species that contribute to the long-term stability and integrity of the mussel bed structure, virtually nothing is known about ecological interactions among the rest. He argued that we "should not be willing to 'experiment' with nature by disrupting such a complex and poorly known system by creating unpredictable results before we understand more fully the consequences of our actions."

Time scale is an important consideration. Broodstock that is protected by the upper size limit may have a lifespan similar to or greater than the career-span of the investigators studying them. Long-term effects of harvest may not be detectable for decades. Rapid development or expansion of a mussel fishery through exploitation of greater areas will only mask effects (through hyperstability of CPUE, harvest levels or detectable population characteristics), particularly when scale of assessment and scale of harvest are radically different. Close examination of harvest effects on individual mussel beds is required.

Local populations (mussel beds) may persist for extensive periods (decades/centuries), and have been demonstrated to require decades to become re-established after catastrophic events (total or virtual extinction). Harvesting practices that remove significant portions of the biomass could be considered as disasters, and the cumulative effects of a few years of repeated harvests may be catastrophic for a local population functioning on a decadal (or greater) time scale.

Precautionary measures for new or developing fisheries recommended in the Technical Guidelines for Responsible Fisheries (FAO 1996) that may be pertinent to development of a sea mussel fishery include:

1) Immediate development of a conservative cap on fishing capacity and total fishing mortality rate. The former could be accomplished by strictly limiting entry into the fishery, and the latter by a conservative total allowable catch. Limiting entry to the fishery should not be problematic. Bed-specific TACs can be developed using the survey protocols and precautionary harvest rates developed above. The information from Cardigan Rocks indicates managing the fishery using only the suggested combination of size limits would not limit the fishery to the recommended harvest

rates. The size limits are still valuable, however, in protecting immature and reproductively valuable size classes from harvest.

2) Establish area closures to limit risks to the resource. Closures provide stock refuges, protect habitat and provide control stocks for comparison with fished stocks. Such closures will be particularly effective for sea mussels, as the mussels are sessile, and can contribute to recruitment in fished areas through dispersal of pelagic larvae. As described above, the proposed fishing area near Port Hardy has numerous parks, ecological reserves, study areas and First Nations reserves that can function as refuges. Care should be taken to ensure adequate refuge areas are protected elsewhere, should the fishery expand.
3) Establish precautionary, preliminary biological reference thresholds. The suggested example is spawning stock biomass less than 50% of the initial biomass. This threshold is used in the B.C. geoduck fishery, and since geoducks and sea mussels have many similar life history traits, this threshold is likely appropriate for sea mussels as well.
4) Encourage fishing in a responsible manner to ensure long-term persistence of a productive stock or other parts of the ecosystem. Consider not only the immediate effects of mussel harvests, but also the potential for increased collateral damage from winter storms closely following mussel harvests.
5) Encourage development of fisheries that are economically viable without long-term subsidies. Economic viability of a sea mussel fishery will remain unknown until product value is established. Once product value is known, an estimate of the available TAC can be used to calculate the total value of the fishery. This can then be compared with fishers expectation of income, and the appropriate number of licenced fishers can be determined. The total value of the fishery can then be used to assess whether the fishery can support the costs of assessment and management.
6) Establish a data collection and reporting system for new fisheries early in their development. Include both fishery-dependent (logbooks, verified landings) and fishery-independent (assessment surveys, experimental harvests) sources of information.
7) Immediately start a research program on the stock and the fishery. Because the life history parameters used to develop precautionary harvest rates are poorly known, and because inadequate knowledge currently exists to use more complex assessment models, research to develop life history and fishery parameters is particularly important. Similarly, evaluating impacts of harvest on the mussel bed community will be virtually impossible until the community, as a whole, is better understood.
8) Take advantage of any opportunities for setting up experimental situations to generate information on the resources. To probe the response of populations to various management frameworks, individual study beds can be exploited using different harvest rates, or different harvest practices, and the results monitored.

Given the concern expressed at the risks involved in harvesting sea mussels, and the ecosystem consequences of overexploitation or irresponsible harvesting, it would be incautious and irresponsible to expand harvests of sea mussels over large areas or through increased participation for several years, until the effects of harvest have been adequately explored on a small scale.

Recommendations

Managers should consider carefully the biological and population characteristics of sea mussels; their keystone role in rocky intertidal community dynamics; the assessment and management programs required to ensure conservation goals are met; the costs of growing water classification, water quality monitoring and product quality monitoring; and the potential value of the fishery (and its ability to fiscally support assessment, management, water and product quality costs) when deciding whether or not to proceed with fishery development. Should managers choose to proceed with commercial fishery development, the following recommendations are presented:

1) Due to the lack of information available to formulate assessment advice, managers should consider confining fishing activities to one or a small number of very small areas, as highly controlled experimental fisheries designed to produce assessment information. Closed areas to be designated as refuges should be identified (parks, ecological reserves, and existing study areas are particularly relevant).
2) Within each fishing area, all harvestable mussel beds should be identified, measured and georeferenced.
3) From the available harvestable beds, specific study beds should be identified. These beds will be used to closely monitor different harvest rates and/or specific harvest practices (haphazard, monolayer, small patch, or seasonal harvest), conduct tagging studies (to establish growth and mortality rates), or examine recruitment, reproductive maturity and/or condition index.
4) Representative beds should be surveyed to develop an area-specific estimate of mean mussel density, which can be expanded by bed area to give a biomass estimate for each bed. Harvesting can then proceed, based on conservative target harvest rates and biomass thresholds.
5) Landings reports should be referenced to individual beds. Given the complexity of the proposed management scheme, an on-site observer/validator/coordinator is recommended.
6) A regular monitoring program is required to assess incidental mortality or bed damage related to harvest, but incurred through natural causes. Randomly selected beds should be assessed annually to confirm harvest rates and monitor changes in biomass or community structure.
7) Managers are recommended to institute a minimum size limit of at least 70 mm to ensure that recruits are allowed to spawn at least once before becoming vulnerable to the fishery.
8) Managers should also consider other options from the available suite of management tactics, including, but not limited to: selective harvest involving hand collection of individual mussels of a specific size range; a maximum size limit to protect mussels that have grown large enough to avoid predation and have considerable reproductive value; rotational harvests; seasonal closures to prevent product waste and decreased market acceptability due to low condition index, to reduce risk of incidental mortality due to

winter storms immediately after harvest, and due to concern for fisher's safety; and/or formal enforcement of responsible harvesting practices.

9) Education of harvesters regarding the requirements and rationale behind responsible harvesting practices (such as individually selecting mussels for harvest, leaving a single layer of mussels on the rocks, targeting the lower intertidal portion of mussel beds for harvests, and/or harvesting small patches leaving most of the surrounding bed intact) is recommended.
10) Investigation of age determination methodologies for sea mussels is recommended. Direct ageing, although expensive and technically challenging, allows more rapid assessment of recruitment, growth and mortality than long-term tagging studies.

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Table 1. Annual landings (t) of mussels (*Mytilus* spp.) in Oregon 1978-1998.

Year	Landings (lb)	Landings (t)
1979	19,068	8.67
1980	60,629	27.56
1981	17,866	8.12
1982	18,372	8.35
1983	28,267	12.85
1984	36,198	16.45
1985	40,168	18.26
1986	37,494	17.04
1987	48,903	22.23
1988	50,656	23.03
1989	65,048	29.57
1990	44,445	20.20
1991	31,931	14.51
1992	22,472	10.21
1993	22,934	10.42
1994	20,009	9.10
1995	25,702	11.68
1996	2,756	1.25
1997	1,919	0.87

Table 2. Estimated natural mortality rates (*M*) and precautionary harvest rates (HR) for theoretical longevity estimates of sea mussels, *Mytilus californianus*.

Longevity (yr)	Estimated *M*	HR (*X*=0.2)	HR (*X*=0.4)
50	0.132	2.6%	5.3%
60	0.113	2.3%	4.5%
70	0.100	2.0%	4.0%
80	0.089	1.8%	3.6%
90	0.081	1.6%	3.2%
100	0.074	1.5%	3.0%

Notes: *M* is estimated using the method of Hoenig (1983), HR is estimated using the Gulland surplus production model, *X* is the scaling factor from the model.

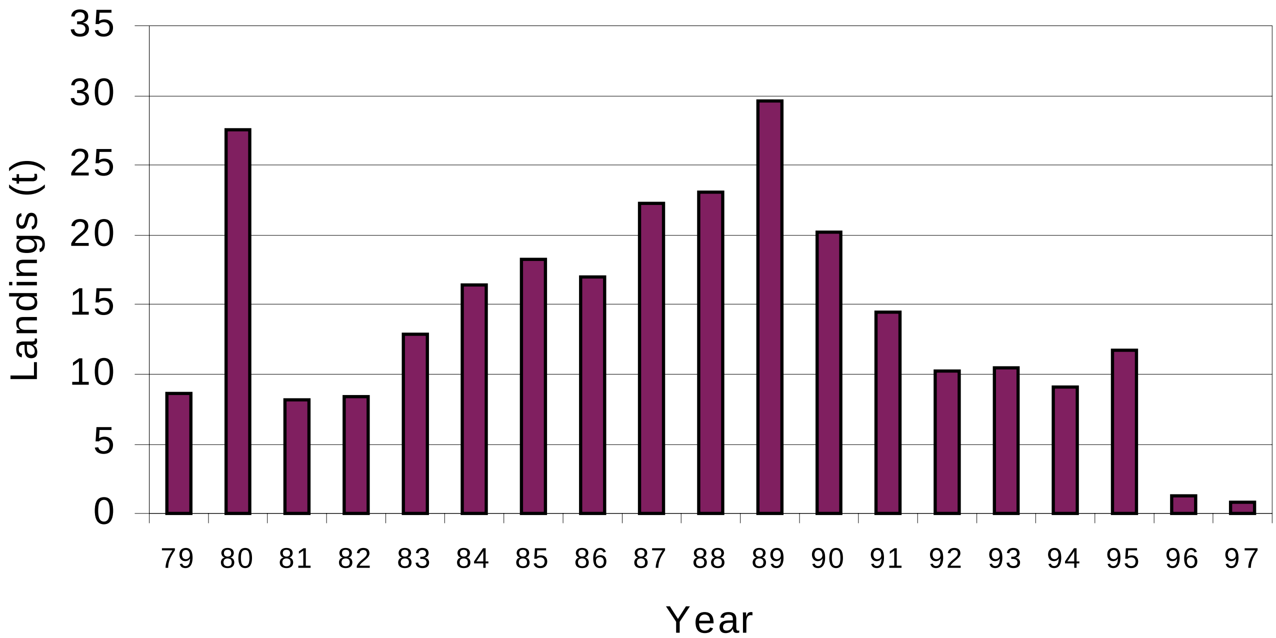

Figure 1. Annual landings (t) of mussels (*Mytilus* spp.) from Oregon, 1979-97.

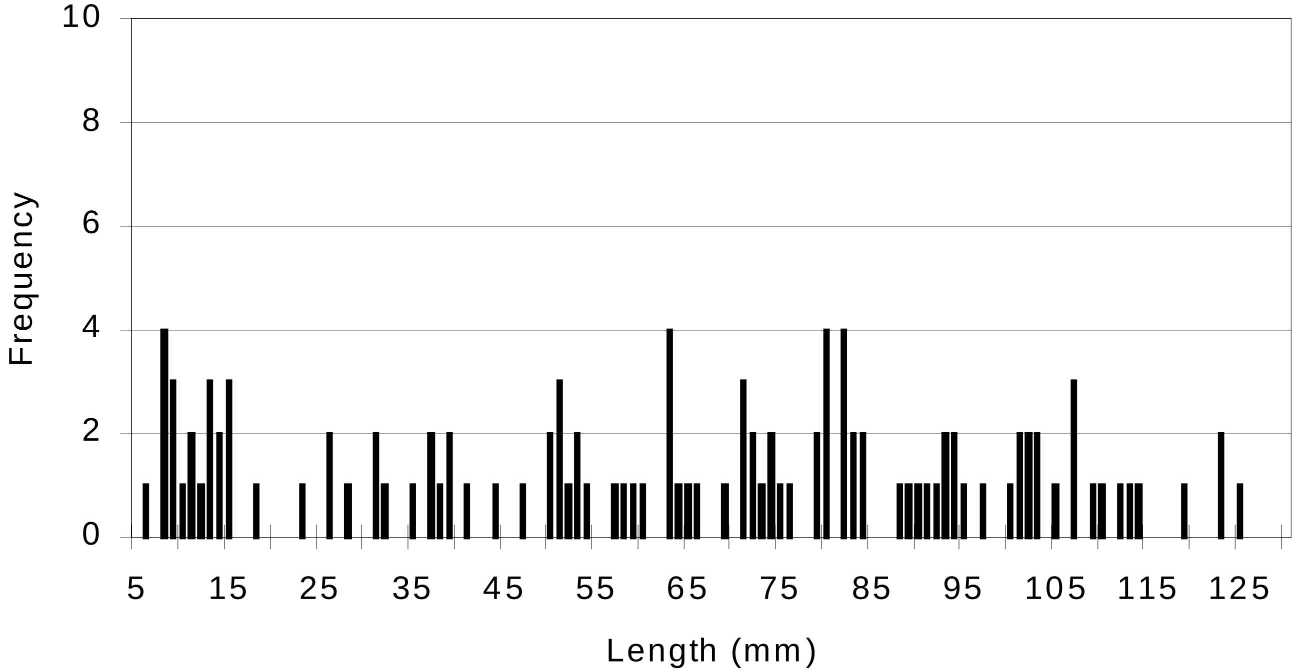

Figure 2. Length frequency of sea mussels, *Mytilus californianus*, collected at Cardigan Rocks, B.C., October 23, 1998.