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An Evaluation of the Feasibility of Using Integrated Pest Management to Control Burrowing Shrimp in Commercial Oyster Beds

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Prepared for the
Washington Department of Ecology
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Battelle

Pacific Northwest Division
Richland, Washington 99352

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EXECUTIVE SUMMARY

This report is the culmination of a two-year study to evaluate the feasibility for developing an integrated pest management (IPM) plan for burrowing shrimp on commercial oyster beds. Two species of burrowing shrimp, *Neotrypaea californiensis* (ghost shrimp) and *Upogebia pugettensis* (mud shrimp), are major pests to the culture of Pacific oysters, *Crassostrea gigas*, in the Willapa Bay and Grays Harbor estuaries of western Washington. Through their burrowing behavior, these indigenous crustaceans resuspend sediments and soften the substrate, which causes the oysters to be buried or to sink into the sediment, thus inhibiting growth or killing the valuable shellfish. Burrowing shrimp also negatively impact other benthic organisms (including clams, eelgrass, and, indirectly, Dungeness crabs) and organisms that depend on these resources. Currently, the pesticide carbaryl is the most commonly used means of reducing burrowing shrimp abundance on oyster beds. However, concern over potential non-target impacts of this pesticide and societal pressure to reduce the use of pesticides in general has created the need to reappraise measures to control burrowing shrimp. An IPM plan would provide a framework for controlling pests based on the ecology of the pest, economics of farming oysters and managing shrimp damage, and the integration of control tactics.

Some of the elements needed for an IPM plan are currently available, but critical information is currently lacking that prevent a "true" IPM plan from being developed. Much is known about the ecology of burrowing shrimp and methods of culturing oysters, several methods of controlling burrowing shrimp have been suggested and evaluated in the field (although not all with scientific rigor), and guidelines have been provided for conducting benefit/cost evaluations of control methods and for developing sampling plans to monitor populations of the shrimp. However, methods currently used to measure burrowing shrimp densities on oyster beds are inaccurate and need to be revised, and it is not presently possible to forecast changes in the abundance of the shrimp. The relationship between the density of shrimp and the damage they cause to oysters is very poorly characterized. It is therefore not possible to develop objective criteria with which to determine when and where to apply control tactics, and new economic injury models for making such decisions must be developed. Although few control methods have been rigorously tested in the field, farmers' have tested several approaches informally, and the only method that has been shown to work consistently and economically is aerial application of the pesticide carbaryl. Thus, an IPM plan for burrowing shrimp is still a long way from being ready. These issues are fully developed in this report chapters, and are summarized below, followed by recommended actions to address the work needed to develop an IPM plan.

Ecology of Burrowing Shrimp: We reviewed the population biology, factors that regulate distribution and abundance, and impacts on other benthic organisms of ghost shrimp and mud shrimp. The two species have different life histories, habitat preferences, burrowing and feeding habits, and different effects upon oysters and other benthic organisms. Thus, these two shrimps have different economic impacts and require different considerations for their management. However, current efforts to control these species treat them as if they were one species and do not use knowledge of their ecologies to develop targeted control tactics. Also, the most widely used method to measure the abundance of burrowing shrimp on oyster beds (i.e., counts of burrow openings within fixed-area quadrats) is seriously flawed. Consequently, existing data are inadequate to determine the relationship between the density of shrimp and damage to oyster crops or to predict rates of shrimp population growth. Lack of information profoundly affects attempts to predict future densities of the burrowing shrimp, to evaluate whether an oyster bed is threatened with economic damage from shrimp, or to set criteria and thresholds to initiate control tactics. Studies are needed immediately to develop accurate population census methods, develop models to project population growth rate, and to measure the relationship between the density of each shrimp species and damage to oysters.

Oyster Culture: The major methods of growing Pacific oysters are bottom culture, floating culture, stake culture, and rack culture. Although bottom culture is the most economical method of growing Pacific oysters, it is also the most vulnerable to burrowing shrimp damage, because the oysters are grown directly on the sediment surface and thus, can sink into the softened substrate or be buried by sediments resuspended into the water column by the shrimp. Floating culture is not practical for Willapa Bay or Grays Harbor because of the paucity of deep water and the vulnerability of floating systems to damage from storms. Longline culture is constrained to using only high productivity, mid- to low-intertidal ground and is vulnerable to damage from burrowing shrimp that undermine the posts that support the lines of oysters. Rack and bag culture is vulnerable to burrowing shrimp damage caused by softening of the substrate, which can cause the racks to sink into the sediment and hinder access by workers on foot to the cultures.

Control Methods: We reviewed and evaluated 15 chemical, biological, and physical methods of controlling burrowing shrimp and cultural methods of minimizing their damage to oyster crops, and suggested several means of integrating control and cultural methods to decrease damage caused by burrowing shrimp to oysters. We concluded that carbaryl pesticide is the most effective and economically practical control method currently available, but that studies should be conducted to evaluate other control methods and the integration of potential control methods. The amount of carbaryl that is used to control shrimp might be reduced by increasing the precision of delivery, such as by ground delivery. Studies are needed to investigate alternative carbaryl delivery systems and to evaluate the benefits and costs of applying carbaryl in spring or fall, particularly just after recruitment of young-of-the-year shrimp. Promotion of eelgrass growth on or adjacent to oyster beds might benefit oyster culture by providing refuge habitat for predators of burrowing shrimp. Growers need incentives to promote eelgrass growth on their private property. Oyster growers and resource agencies should actively support efforts to conserve and enhance natural populations of finfish predators of burrowing shrimp, such as sturgeon, salmonids, and staghorn sculpin. Oyster growers and other entrepreneurs should investigate expansion of existing markets or creation of new markets (such as seafood products) for burrowing shrimp. Several control methods that use new techniques or specific timing regimens deserve further investigation. These include shell pavementing, dredge harvesting, sediment compaction, and pesticides other than carbaryl. We suggest several ways in which control methods and cultural practices could be integrated such as combinations of chemical control, shell pavement, predator habitat enhancement, physical barriers, timing of control actions (chemical, biological, or physical) with shrimp recruitment, sediment compaction (or harrowing), shrimp harvesting, diking and damming, and salinity variances. The methods that offer the greatest promise to control burrowing shrimp are pesticides (carbaryl and possibly abamectin and imidacloprid), predator enhancement, shell pavementing, sediment compaction or sediment disturbance (i.e., harrowing or dredge harvesting), and sediment barriers. Cultural methods that could best reduce economic damage to oyster crops are reinforcement of longline structures, harvest of burrowing shrimp, and culture of other species that are more tolerant of burial and softened sediments (such as Manila clams). As a whole, the growers and other experts felt that carbaryl pesticide, predator enhancement, and shrimp harvest would have either no long-term detrimental impacts or long-term beneficial impacts to environmental and human resources. Methods that were judged to have the greatest potential for long-term negative impacts were other pesticides, sediment barriers, clay injection, water jets, and Electro-shocking/ultrasound.

Decision Criteria: The current threshold for application of carbaryl to control burrowing shrimp on oyster beds (burrow hole count of 10 b/m^2) has been used since the 1970s. However, we found that the basis for this threshold is seriously compromised for three biological and institutional reasons: 1) the burrow count data is collected in early spring when the relationship between the number of burrows and the abundance of burrowing shrimp is highly unreliable; 2) the relationship between the density of burrowing shrimp and damage to oyster crops has not been quantified; and 3) the threshold does not distinguish between the numbers of burrows made by each of the two species of shrimp. Thus, the threshold of 10 b/m^2 is not an accurate predictor of the damage that burrowing shrimp cause to oyster crops and is inappropriate for use as a decision criterion; immediate efforts are required to establish an accurate threshold.

We were unable to estimate treatment thresholds using economic injury level (EIL) or economic threshold (ET) models for two reasons: 1) there are critical knowledge and data gaps relative to the relationship between density and economic impact and relative to population census statistics, and 2) the existing EIL/ET models developed for terrestrial IPM plans do not account for unique aspects of the interactions between the ecology of the shrimp and the culture of oysters, nor do they include consideration of the costs of the control methods to other environmental resources and services, which are highly valued within the Willapa Bay and Grays Harbor estuaries. Specific EIL/ET models that characterize the oyster-shrimp-control interactions for different aspects of oyster culture will provide growers and environmental regulators with greater flexibility in deploying and managing control tactics. Once methods are developed for accurately censussing burrowing shrimp populations and criteria are developed for the major aspects of oyster culture, then sampling plans can be developed to support each critical pest threshold.

Critical Information and Research Needs: We identified several important information needs that would help in the development of the IPM plan. The five most critical information and research needs are:

1. Development of methods and protocols to accurately census burrowing shrimp populations;

2. Quantify the relationship between the density of burrowing shrimp populations and damage to oyster yield;
3. Development of alternative methods and timing for delivery of carbaryl;
4. Understanding the underlying reasons for regional increase of burrowing shrimp populations; and
5. Development of objective decision-making criteria to determine where and when to deploy control tactics.

We discussed additional information and research needs in the areas of the ecology of burrowing shrimp, cultural practices, methods to control burrowing shrimp, and the development of decision criteria and thresholds.

Implementation of an IPM Plan: We provide the following suggestions that oyster growers and resource agencies could use to implement an IPM plan for burrowing shrimp:

- Communicate the IPM plan to growers, resource agencies, and the public.
- Identify an individual to coordinate the IPM Plan.
- Establish a state-owned and grower-operated demonstration farm.
- Improve relationships among stakeholders through education, open forums, and working groups to improve trust, respect, and cooperation.
- Improve respect for "local" knowledge.
- Provide resources to implement the IPM plan.

In the interim, there is much the stakeholders can do to progress toward an IPM plan. In addition to the recommendations outlined above, growers and regulators can take the following immediate steps. Growers should:

- be more rigorous in collecting information on the costs to farm each of their beds and the yields recovered from each bed,
- track the abundance of burrowing shrimp species on their oyster beds and monitor changes in the coverage of eelgrass on these beds;
- investigate methods of ground application of carbaryl; and
- investigate the integrated control practices suggested in this report.

State and Federal regulatory agencies should:

- reduce the bureaucracy associated with carbaryl spray permits so that the permit-evaluation process is shortened;
- help growers to develop alternative strategies for controlling burrowing shrimp by easing restrictions on tideland habitat manipulations;.
- continue to support research into development of alternative control methods, improved shrimp census methods, the damage/density relationship between oysters and burrowing shrimp, and development of scientifically-sound decision criteria.

Dialog between growers, regulators, the local community, and other interested people must continue, and efforts must be re-doubled to increase trust among these parties. All of these parties seem to share a serious interest to reduce the economic impacts of burrowing shrimp, and maintain a sustainable oyster industry and a sustainable estuarine ecosystem. Forums such as the Burrowing Shrimp Advisory Committee provide an excellent opportunity to work on improving communication and relationships among stakeholders.

Further Development of the IPM Plan: An IPM plan must have capacity and capability to change and improve over time. By regularly incorporating new knowledge into the plan, and by regularly disseminating improvements to the plan, the oyster growers and resource agencies will see steady progress toward the IPM plan's goal of maximizing profit from the production of oysters while minimizing deleterious impacts to other environmental or human resources.

1.0 INTRODUCTION

Two species of burrowing shrimp, *Neotrypaea californiensis* (ghost shrimp) and *Upogebia pugettensis* (mud shrimp), are major pests to the culture of Pacific oysters, *Crassostrea gigas*, in the Willapa Bay and Grays Harbor estuaries of western Washington. Through their burrowing behavior, these indigenous crustaceans resuspend sediments and soften the substrate, which causes the oysters to be buried or to sink into the sediment, thus inhibiting growth or killing the valuable shellfish. Oyster growers have reported an increase in burrowing shrimp population size and geographic distribution within the estuaries since the 1950s. It has been estimated that nearly 3000 acres of oyster grounds (i.e., ~30% of presently farmed acreage) in both estuaries combined could be reclaimed for oyster production if burrowing shrimp were removed (Burrowing Shrimp Control Committee [BSCC] 1992). Various mechanical and chemical control measures have been investigated by oyster growers over the last 40 years, and currently, the pesticide carbaryl is the most commonly used means of reducing burrowing shrimp abundance on oyster beds. However, concern over potential non-target impacts of this pesticide and societal pressure to reduce the use of pesticides in general has created the need to reappraise measures to control burrowing shrimp.

One approach for managing burrowing shrimp damage is integrated pest management (IPM), which provides a framework for controlling pests based on the ecology of the pest, the economics of producing the crop, the economics and efficacy of chemical, biological, and physical control tactics, and methods of producing the crop. For the control of ghost shrimp and mud shrimp, a working definition for the IPM plan is:

> A sustainable, site-specific, and ecologically based pest management plan that integrates knowledge of the life history and ecology of both species of burrowing shrimp, their natural predators and competitors, chemical, biological, and physical control tactics, cultural practices, and all other suitable techniques to maintain populations of burrowing shrimp at population densities below economically injurious levels.

We view IPM as a framework for objectively determining appropriate tactics to control pests in an economically and ecologically defensible manner, with sufficient flexibility that decisions can be developed for specific parcels of farmland. An IPM plan utilizes information on the population biology of the pest, methods to accurately census the density of the pest population, the economics of the pest damage to the crop, methods to reduce the risk of pest damage to the crop, and the vulnerability of the pest to various pest-control tactics. This information is combined to produce a sampling plan to track pest damage to the crop, objective thresholds of pest density at which control measures must be applied, and an array of pest-control tactics that selectively target the most vulnerable life stages or destructive behaviors of the pest. IPM is imperfect, relying on existing knowledge of the pest biology, simplified economic and population models, and data of variable quality; as such, it is subject to unpredictable ecological, climatic, and human variables. An IPM plan has a dynamic nature, such that it must change as knowledge is gained about the ecology of the pests, the economics of farming, and the methods of managing the pests.

In this study, we reviewed the elements needed to develop an IPM plan to control burrowing shrimp on commercial oyster beds in Willapa Bay and Grays Harbor. We reviewed the physical and ecological environment of Willapa Bay and Grays Harbor where burrowing shrimp and oyster farming occur, the methods of growing oysters, and the ecology of burrowing shrimp. We then review and propose practices for managing burrowing shrimp damage, criteria for implementing shrimp management practices, and means of monitoring pest density in advance of initiating control tactics. If sufficient information was available, we will combine this information into an IPM plan as outlined above; if not, we will identify the critical data and knowledge gaps, and suggest methods for obtaining them. Our analysis focused on evaluating existing information, but where data are not available, we also hypothesized possible approaches to various issues. This study was not designed to be an environmental impact assessment of oyster culture or of methods used to control burrowing shrimp. This study operated from the premise that oyster farming is an established practice within Willapa Bay and Grays Harbor, that burrowing shrimp are a pest to oyster culture, and that damage caused to oyster yield by burrowing shrimp needs to be managed in order that commercial oyster farming can remain profitable.

2.0 METHODS

Development of the burrowing shrimp IPM plan involved analysis of the ecology of the two burrowing shrimp species and their impacts on oyster culture (both on- and off-bottom culture), analysis of natural processes that control burrowing shrimp populations and distributions, assessment of methods to measure burrowing shrimp abundance and their impacts on oysters, and analysis of the effectiveness and economics of existing and potential pest control practices. The Battelle Marine Sciences Laboratory (Battelle) team sought to provide a set of tools for objectively setting thresholds for application of control measures (based on shrimp abundance, the economics of shrimp-induced damage, and the costs of implementing the control tactic), for objectively comparing existing and proposed control practices on a benefit-cost basis, and for periodically updating the IPM plan. We also proposed to provide IPM-based protocols for controlling burrowing shrimp based on previous or existing control practices. We were directed to not develop new control practices, conduct field studies to evaluate the cost-effectiveness of current control practices, nor to conduct research to evaluate practices that are currently under development. Thus, our information gathering was limited to reviewing the literature and conducting interviews, and our analyses and evaluations were limited to existing data sets and information obtained from the reviews and interviews.

2.1 LITERATURE REVIEWS

We reviewed scientific literature published in peer-reviewed journals, theses, and reports concerning the life history of ghost shrimp (*Neotrypaea californiensis*; formerly *Callianassa californiensis*) and mud shrimp (*Upogebia pugettensis)*, natural controls of burrowing shrimp abundance and distribution, the physical nature and ecology of the Willapa Bay and Grays Harbor estuaries, oyster farming practices, methods of sampling burrowing shrimp density, methods of controlling burrowing shrimp populations, and environmental injury and environmental threshold models available for IPM. These reviews are integrated into sections of this report concerning each of these issues.

2.2 INTERVIEWS

We conducted both informal and formal interviews with people knowledgeable about oyster farming and aquaculture, burrowing shrimp ecology and management, estuarine ecology (particularly of Willapa Bay and Grays Harbor), IPM theory and practice, environmental regulation (particularly for Washington State estuarine resources), and pesticides. Informal interviews consisted of in-person and telephone conversations or meetings with oyster growers, academic, government, and private-sector researchers, environmental regulators, and non-government organization biologists.

Formal interviews were limited by resource constraints to twelve oyster growers from Willapa Bay and Grays Harbor and eight expert non-growers. Each person was interviewed in-person and given a follow-up questionnaire to fill out at his/her leisure. People interviewed were selected from recommendations provided by Washington Department of Ecology (WDOE), U.S. Environmental Protection Agency (EPA), oyster growers, and the Willapa Alliance. Growers using bottom culture only (6), longline culture only (3), and combinations of bottom culture, longline culture, and rack and bag culture (3) were included in the interviews. We selected non-grower experts who were knowledgeable about the Willapa Bay and Grays Harbor estuaries and the issues surrounding burrowing shrimp management. These experts represented estuarine biologists (academic, government, tribal, and private), harvesters of other natural resources in or adjacent to the estuaries (i.e., cranberries and crabs), environmentalists, and state regulators. Some individual experts represented more than one category. Growers and non-growers were questioned regarding their involvement and practices in the oyster industry, familiarity with and opinions about various methods to control burrowing shrimp populations, and the environmental impacts of burrowing shrimp and methods of controlling them (Appendices A and B). In addition, growers were asked about their practices of monitoring shrimp population density, experience with different methods of controlling shrimp, and economic aspects of oyster farming.

Whereas information provided by the oyster growers was business-sensitive, anonymity was assured to all who were interviewed, and all "raw" interview and questionnaire records were destroyed after the responses were tabulated. Furthermore, the tabulated responses were also destroyed once we summarized responses to our questions. These summaries consisted of the average and the ranges of responses to both quantitative and qualitative questions, estimated for growers and non-growers separately.

2.3 BURROWING SHRIMP POPULATION MODELS

Population growth models for burrowing shrimp were developed to provide the means to project the future densities of ghost shrimp and mud shrimp on oyster beds. Such models could provide growers with advanced warning of potential adverse impacts to oyster production. Two approaches were taken to construct population models. The first approach used records of annual burrow counts and shrimp densities from state surveys and experimental studies to calculate the net annual rate change in burrow or shrimp density. The second approach used recruitment and mortality data from experimental studies to estimate the abundance of adult (1-yr old and older) ghost shrimp.

2.3.1. Net Population Growth Model. We were provided with burrow count census data that had been collected between 1963 and 1994 by the Washington Department of Fish and Wildlife (WDFW) as part of their program to certify private and state-owned oyster beds for carbaryl treatment (Dennis Tufts, pers. comm.). Independent estimates of population growth rate were obtained from Dr. Brett Dumbauld (WDFW), who censussed populations of ghost shrimp and mud shrimp over 2- to 8-year periods in experimental plots that were treated or not treated (control) with carbaryl. Net annual population growth rates (burrows/m^2/y - WDFW and Dumbauld studies; shrimp/m^2/y - Dumbauld studies only) were estimated as the difference in burrow or shrimp density between census years that did not receive carbaryl treatment, divided by the number of years between censuses.

The WDFW data set included information on oyster bed location, ownership, the acres treated with carbaryl, the density of burrows per unit area, the identity of burrowing shrimp, and the census year. The data set was sorted by bed location, ownership, census date, and burrowing shrimp species. Records lacking burrow-count data or unambiguous bed identification numbers were not included in the analysis. Cases in which one burrow count was recorded as representative of multiple beds was scored as each bed having that density of burrows. Current and former WDFW personnel cautioned that the burrow-count data contained in the WDFW data set were of variable quality, as many counts were approximations, especially if the burrow density exceeded 10 burrows/m^2 (b/m^2), which is the current threshold used to qualify beds for spraying with carbaryl (B. Dumbauld and D. Tufts, pers. comm.). Furthermore, many of the oyster beds censussed by WDFW contained both ghost and mud shrimp, but because only total numbers of burrows were recorded, we could only estimate the net rate of change for the mixed population in those beds. Additionally, the data were collected during spring when shrimp activity is low and the density of burrows is a poor predictor of the true density of shrimp. Finally, we also learned that the data prior to 1984 were measured as b/yd^2, and thereafter as b/m^2, but that the WDFW data set was not adjusted for the change in units. Thus, the population growth rate estimates based on the WDFW data set contain several sources of inaccuracy.

2.3.2 Recruitment and Mortality Estimates. K.L Feldman (School of Fisheries, University of Washington) and D.A. Armstrong and B.R. Dumbauld (WDFW) estimated recruitment and mortality rates for *N. californiensis* from population censuses on experimental plots in Willapa Bay Harbor estuaries. Recruitment was measured as the density of young-of-the-year (YOY) ghost shrimp collected in the upper 15 cm of sediment during the fall (September or October) (Dumbauld, unpublished data). Recruitment and mortality estimates were also derived from cohort-analyses of population structure data obtained in a 3-yr (i.e., 1989-1992) study of carbaryl efficacy at a Palix River site in Willapa Bay (Dumbauld 1994). We used the data from plots treated with the highest dosage of carbaryl (i.e., 5.6 kg ha^{-1}), which killed >90% of the ghost shrimp, thereby simplifying tracking the abundance of the 1989 year-class through time. Cohort analysis was conducted using the MIX program (Release 2.3, Icthus Data Systems, MacDonald and Pitcher 1979) which identified age classes by fitting lognormal components to length-frequency histograms. An assumption in estimating proportions of shrimp in each age class was that badly damaged, unmeasurable, and un-sexable shrimp were equally represented among ages and between sexes. Because the MIX program often converged on more than one possible set of components, information on shrimp growth rates and recruitment of multiple cohorts was used to choose the best scenario (Bird 1982; Dumbauld et al. 1996). Once numbers of shrimp were determined by age class, an estimate of natural mortality was derived based on linear regression of natural log-transformed abundances of the 1989 year-class from 1990 through 1992.

3.0 PHYSICAL AND ECOLOGICAL DESCRIPTION OF THE ESTUARIES

3.1 PHYSICAL CHARACTERISTICS OF THE ESTUARIES

Willapa Bay and Grays Harbor estuaries are located along the southwest coast of Washington State, immediately north of the mouth of the Columbia River (Fig. 3.1). These are two of the major estuarine systems of the U.S. Pacific Coast. Several previous reports described the physical and ecological characteristics of both estuaries (i.e., for Willapa Bay, see USACE 1976, Shotwell 1977, and WDF/WDOE 1985; for Grays Harbor, see WDOE 1983, and WDF/WDOE 1985). Summarized below are some of the salient characteristics of each estuary that are relevant to oyster farming and the distribution of burrowing shrimp.

3.1.1 Willapa Bay Estuary. Willapa Bay estuary is oriented north-south, with a length of ~25 mi and maximum width of ~6 mi. Aerially, the estuary encompasses approximately 79,000 acres at mean high water. It is separated from the Pacific Ocean by a long barrier spit, North Beach Peninsula, that extends north from the mouth of the Columbia River. The mouth is a broad, shallow pass, approximately 6 mi wide, located at the northwest corner of the bay; it is an area of shifting sand shoals with the most consistent channel located near Cape Shoalwater at the north. Eight rivers (the Cedar, North, Willapa, Bone, Niawakum, Palix, Nemah, and Bear rivers) and many smaller creeks enter Willapa Bay, draining a complex of watersheds totaling more than 720 square mi.

More than 50% of the tidal portions of the estuary are exposed at low tide (Fig. 3.2), and much of the remaining subtidal area is very shallow at low tide (<6 ft). Less than 15% of the estuary is deeper than 20 ft (Anima et al. 1989). The maximum tidal range is approximately 12 ft (4 m). The extensive tidal flats can extend more than a mile from shore. Adjacent to the tidal flats and shallows are a few deep channels that are maintained by tidal currents, stream runoff, and dredging. Shallow tidal creeks (<3 ft) drain water from tide flats into the larger channels; these creeks are highly ephemeral and many go dry at high tide (Fig. 3.3). The locations of tidal flats, shorelines, creeks, and channels in Willapa Bay are extremely dynamic, caused by complex tidal currents and storm-driven currents and waves. The North Beach Peninsula is a low barrier that protects most of the estuary from direct exposure to the Pacific Ocean but does not block the strong winds accompanying the frequent storms that hit this region. Storms with hurricane-force winds hit the estuary almost every year. The geomorphology of the estuary is subject to rapid change (caused by floods and tsunamis; Shotwell 1977), as well as long-term continuous change (the mouth of the estuary has shifted north at least 3 km over the last 100 yr; Clifton 1980).

From the mouth of the estuary into its central part and along most of the deep channels, sediments are well-sorted fine sand, with pockets of mud forming locally in depressions or in the lee of high areas that deflect waves (Fig. 3.4). In the upper and lower portions of the estuary and along the banks of the rivers, intertidal and supratidal sediments are muds and sandy muds. The sediment characteristics in each of these locations are determined by tidal currents, storm currents, sediment transport from the watersheds, and erosion of the Pleistocene cliffs to the east and south of the estuary (Clifton and Phillips 1980; Clifton 1983; Anima et al. 1989). Additionally, bioturbation by ghost shrimp winnow fine-grained material from tidal flats, thus creating a well-sorted sand substrate.

Complete flushing of the water in Willapa Bay is reported to take 20 to 40 days and is affected by the tidal range, strength, and direction of prevailing winds and the water flow rates of the rivers (Kincaid 1968, USACE 1976). The water in Willapa Bay can be strongly affected by offshore conditions: in summer, high-salinity up welled waters can be driven in by northwest winds and increase the salinity of the bay, whereas in winter, low-salinity waters from the Columbia River plume can dramatically lower the salinity of the bay (USACE 1976; L. Bennett, pers. obs.). Salinity ranges from 7‰ to >30‰ within Willapa Bay, with salinities decreasing up the river drainages and during the rainy season. Oyster growers and naturalists report that water in Willapa Bay occasionally become nearly fresh as a result of freshets and floods (and possibly the presence of very low-salinity waters offshore from the Columbia River plume) (Kincaid 1968; L. Bennett, pers. obs.). Annual rainfall in the area can range from 44 in. to >110 in., with greatest rainfall occurring between October and March (Kincaid 1968). Water temperatures range annually from 3°C to 21°C, and are usually warmer toward the head of the estuary than at the mouth caused by solar heating of the tidal flats and the shallowness of the bay (Kincaid 1968; USACE 1976). Obviously, water temperatures are also warmer in summer months than in winter months. Water in Willapa Bay is usually turbid because of a combination of natural (wind, waves, currents, and runoff) and human influences (upland erosion, dredging). Turbidity is typically higher at the surface than at depth and is often higher during the winter, caused by storm-related runoff and waves (WDF/WDOE 1985).

3.1.2 Grays Harbor Estuary. Grays Harbor estuary is oriented east-west, with a maximum length of ~32 miles and a north-south width of ~13 miles (Fig. 3.5). The entrance is bounded on the north and south by two sandy peninsulas (Point Brown to the north, Point Chehalis to the south), which separate the estuary from the Pacific Ocean. Aerially, the estuary encompasses ~54,700 acres at mean high high-water (MHHW), of which ~63% are exposed at low tide (Loehr and Collias 1981; Iribarne et al. 1995). Six rivers flow into Grays Harbor estuary: Chehalis, Wishkah, and Hoquiam Rivers to the east, Humptulips River to the north, and the Elk and Johns Rivers to the south. Urban and industrial activities in the cities of Aberdeen, Hoquiam, and Cosmopolis have contributed to water pollution and poor water quality, particularly in the eastern portions of the estuary. Because of this, oyster farming is limited to the tidelands adjacent to the central and south-western portions of the estuary.

Extensive intertidal flats, broken up by numerous tidal creeks, are the predominant geological features of Grays Harbor (Fig. 3.5). One major channel (North Channel) is actively dredged to depths of -45 ft for navigation and is the major shipping channel for Aberdeen, Hoquiam, and Cosmopolis. Two other channels (Middle and South Channels) are not routinely dredged and have depths up to -25 ft. Furthermore, the banks of many of the tidal flats in the central and south-western portions of the estuary have a moderately steep profile leading down to tidal creeks and channels. This restricts some of the most productive oyster growing ground to a relatively narrow band along the margin of the tide flats (Brady Engvall, Brady's Oysters, pers. comm.).

Tidal currents dominate the mixing and flow characteristics of waters within Grays Harbor estuary (Loehr and Collias 1981; WDOE 1983). Wind, tides, coastal upwelling, and river flow combine to create dynamic and complex movements of water within the estuary. In summer, low river flow rates and the large volume of the estuary combine to produce relatively poor circulation in the central portion of the bay and, consequently, pollutants may not be efficiently flushed from the bay. Loehr and Collias (1981) estimated a flushing time of 5 days for the bay. Maximum river flows and upland runoff occurs in December and January when rainfall is greatest. Salinity is highly variable spatially and temporally within Grays Harbor. Salinity in summer ranges from 5‰ to 15‰ near Aberdeen, 20‰ to 30‰ in the central bay, and to >30‰ at the mouth of the bay (Loehr and Collias 1981). In winter and spring, salinity in the inner bay ranges from 0.5‰ to 15‰, from ~5‰ to 20‰ in the central and western parts of the estuary, and 20‰ to 33‰ at the mouth of Grays Harbor. Water temperature tends to be less variable spatially than seasonally within the estuary. In winter, water temperatures range from 2°C to 6°C in the inner harbor, and from 5°C to 8°C in the main portion and entrance to the bay. Conversely, in summer, western bay temperatures average ~15°C, whereas inner-bay temperatures average ~19°C as a result of relatively poor water circulation (Loehr and Collias 1981).

As with Willapa Bay, Grays Harbor experiences gale-force storms several times per year, typically between November and March. These storms add to the dynamic nature of the estuary and are responsible for rapid transport of sediment, creation and destruction of tidal creeks, lateral movement of main channels, flooding, and short-term changes in water chemistry (particularly salinity, temperature, and turbidity). Physical structures placed within the estuary (e.g., for oyster culture) must be able to withstand these forces.

3.2 Ecological Characteristics Common to Both Estuaries

WDF/WDOE (1985) provides summaries of the vegetation, fish, waterfowl, and mammals found within Willapa Bay and Grays Harbor. The two estuaries are very similar in many of these aspects, with the principal difference that *Spartina* marshes are far less extensive in Grays Harbor than in Willapa Bay. Thus, this report will focus on the common ecological elements of both bays, and interested readers should refer to Shotwell (1977), Kalinowski et al. (1982), WDOE (1983), WDF/WDOE (1985), WDF/WDOE (1992), and sources cited therein for addition details.

3.2.1 Vegetation. Eelgrass (*Zostera marina* and *Z. japonica*) is the dominant rooted plant within both estuaries, occurring on intertidal and shallow subtidal flats between -3 ft and +6 ft mean low low-water (MLLW). Eelgrass forms large, dense beds, recognized as important habitat for many invertebrates (including Dungeness crab) and juveniles of many fish species, and is spawning habitat for Pacific herring. Cordgrass (*Spartina alterniflora*), introduced to the Pacific Coast with shipments of seed oysters from the U.S. Atlantic coast, is classified as a noxious weed in Willapa Bay, as well as to the rest of the U.S. west coast. *Spartina* marshes are expanding within Willapa Bay, out-competing native shoreline vegetation, and elevating the tide flat by enhancing rates of sediment deposition within the beds (Ron Thom, Battelle Marine Sciences Laboratory, pers. comm.). Several macroalgal species can be found on the tidal flats of the estuaries, with two dominants in oyster beds being *Ulva* spp. (sea lettuce) and *Polysiphonia* spp. (red algae).

3.2.2 Benthic Invertebrates. Both species of burrowing shrimp (i.e., ghost shrimp, *N. californiensis*, and mud shrimp, *U. pugettensis*) are indigenous to these estuaries and are the dominant infaunal invertebrates on many tide flats. The ecology of these species is discussed extensively in Chapter 4. Dungeness crab (*Cancer magister*) are common in both estuaries and use coastal estuaries as habitat for growth and maturation as juveniles. Young crabs are attracted to physical structures on the tide flats (such as oysters and eelgrass), probably for both foraging opportunities and protection from predators. Thus, abundances of Dungeness crabs is usually higher within oyster beds than on tide flats dominated by burrowing shrimp (Doty et al. 1990). Dungeness crabs are a major commercial and recreational fishery in Washington State. Other common benthic invertebrates on the tide flats include bivalves (*Macoma balthica, M. nasuta, Clinocardium nuttallii, Tapes japonica, Mya arenaria, Mytilus edulis*), polychaete worms (*Abarenicola pacifica, Harmothoe imbricata, Nephtys spp., Nereis spp., Capitella capitata, Armandia brevis, Heteromastus filiformis*), crabs (*Hemigrapsus oregonensis, H. nudus, Cancer productus, C. oregonensis*), shrimp (*Crangon spp.*), amphipods (*Corophium spp., Eohaustorius spp.*), isopods, cumaceans, nemertean worms, and burrowing anemones. Oyster beds have been shown to harbor a high species diversity of benthic invertebrates, especially in comparison to tide flats dominated by burrowing shrimp (Brooks 1993, 1995).

3.2.3 Fish. Tributaries of Willapa Bay and Grays Harbor provide spawning grounds for chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), chum salmon (*O. keta*), steelhead (*O. mykiss*), and searun cutthroat trout (*O. clarki clarki*). Hatchery-raised salmonids are also produced on several of the rivers and are released into the estuaries. Salmon migrate through the estuary at various times through the year (Fig. 3.6), using it for foraging and refuge while they undergo physiological changes in transition from a freshwater to saltwater existence. Other species of finfish found in these estuaries include green and white sturgeon, Pacific herring, anchovies, longfin smelt, surf smelt, American shad, juvenile lingcod, surf perch and sea perch (several species), gunnel, sand lance, greenling, sculpin (several species), English sole, sand sole, sand dab, and starry flounder (Posey 1986b). Sturgeon and sculpins are reported to be predators of burrowing shrimp (Brad James, WDFW, pers. comm.; Posey 1985, 1986b).

3.2.4 Birds. A diverse fauna of migratory and resident waterfowl and shorebirds use the Willapa Bay and Grays Harbor estuaries. Species of waterfowl include American wigeon, mallard, green-winged and cinnamon teal, northern shoveler, greater and lesser scaup, white-winged and surf scoters, ruddy duck, wood duck, red-breasted merganser, canvasback, pintail, bufflehead, western grebe, Pacific black brant, Canada goose, and white-fronted goose. As many as 24 species of shorebird use the estuaries, many of which are migratory. Some of the more numerous species include Western and least sandpiper, dunlin, great blue heron, short-billed and long-billed dowitcher, and sanderling. Gulls and terns are also common in these estuaries, including western gull, glaucous-winged gull, and Caspian tern. Other waterbirds found in the estuaries include loons, grebes, shearwaters, petrels, cormorants, brown pelican, marbled murrelet, and rhinoceros auklet. These birds feed on aquatic plants, benthic invertebrates, bait fish, and juvenile fish. Gulls and herons have been observed feeding on burrowing shrimp that have exited their burrows (Posey 1985; T. DeWitt, pers. obs.). Summaries of some waterbird foraging studies can be found in WDF/WDOE (1985). Several species of raptors forage on birds, fish, and carrion within the estuaries, including bald eagle, northern harrier, redtailed hawk, sharpshined hawk, Cooper's hawk, osprey, peregrine falcon, and short-eared owl.

3.2.5 Marine Mammals. Harbor seals are the most numerous resident marine mammals in both estuaries. They feed on fish, including salmon, and crab, and intertidal sandbars are used as haulouts. California sealions and harbor porpoise are also occasionally seen. Gray whales occasionally enter the estuaries and are reported to feed on burrowing shrimp (Weitkamp et al. 1992).

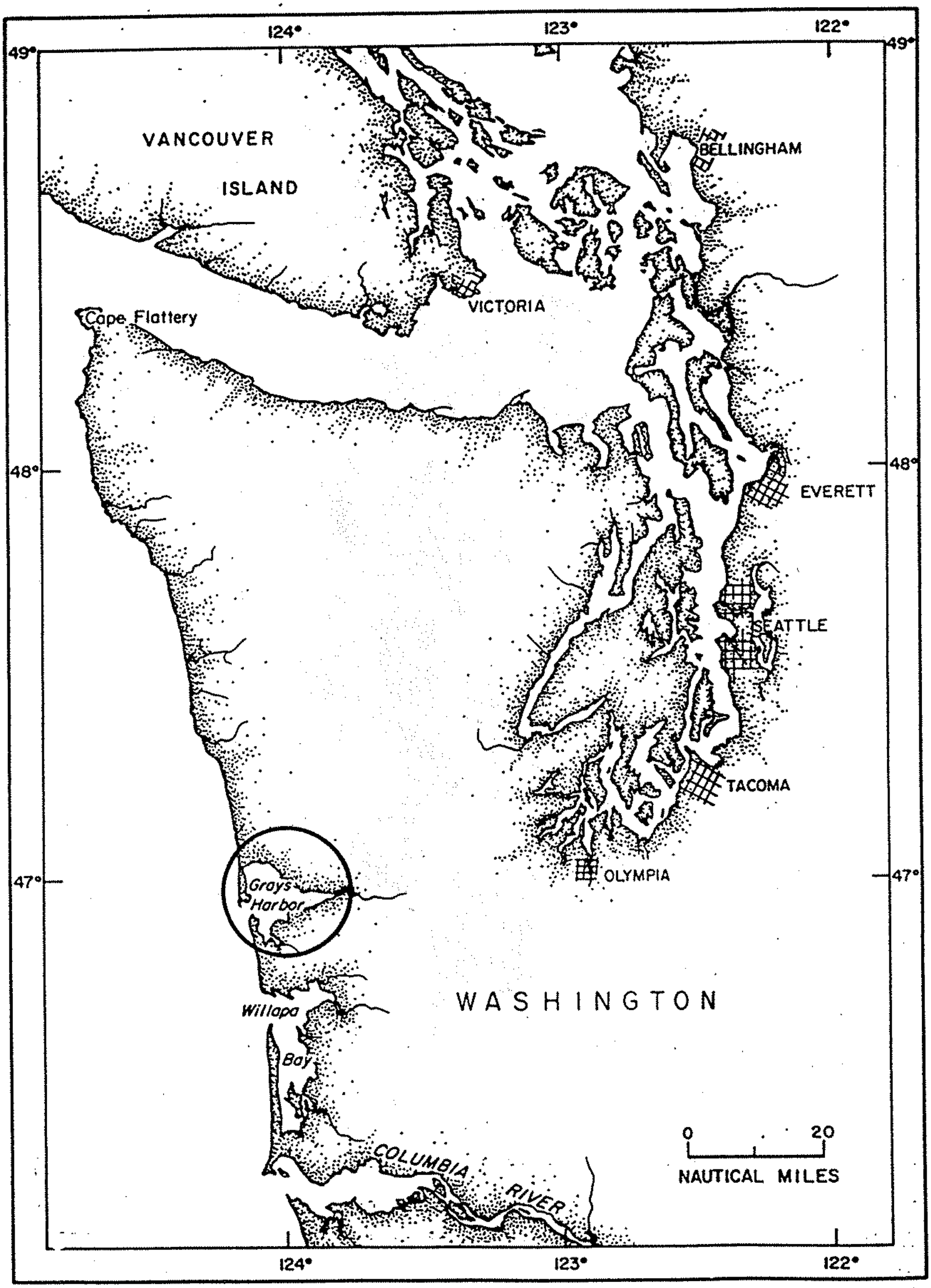


Figure 3.1 Location of Willapa Bay and Grays Harbor estuaries (Loehr and Collias 1981).

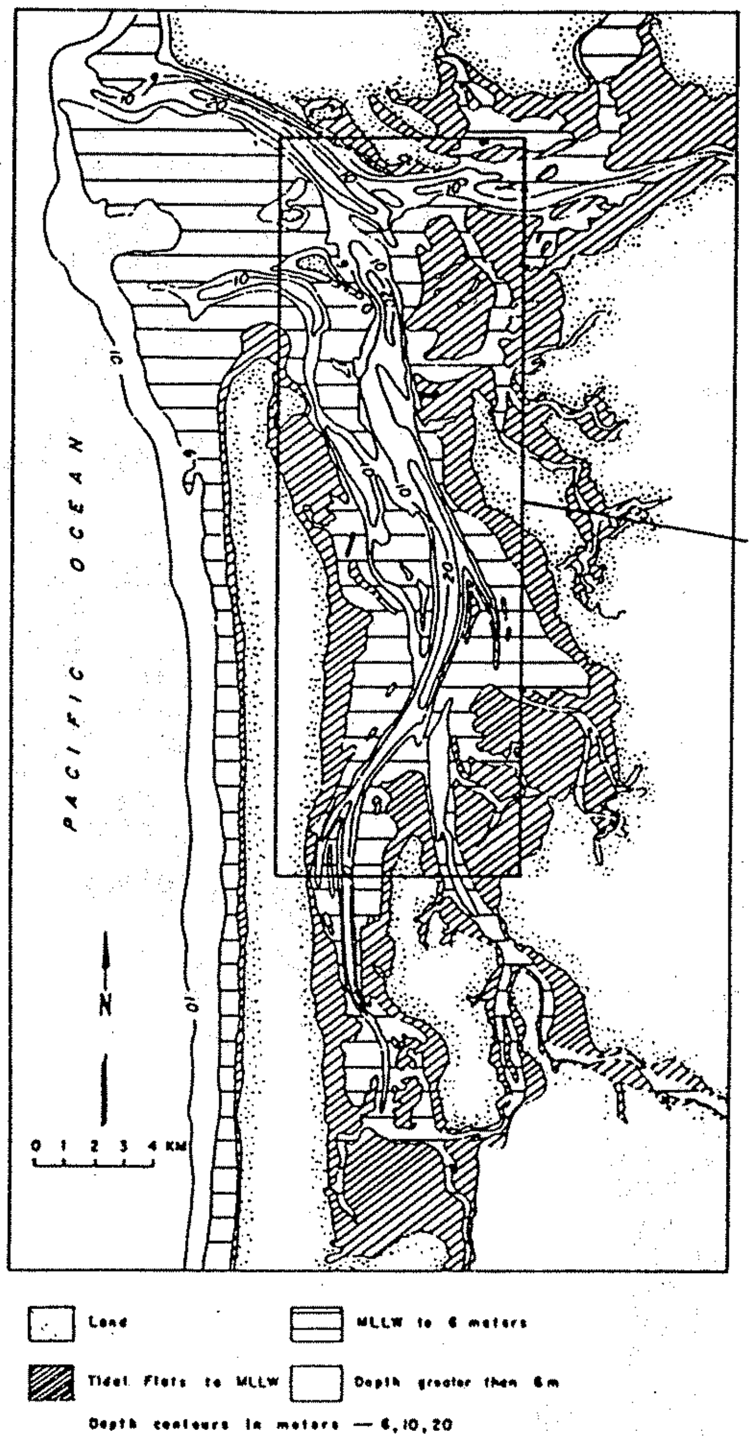


Figure 3.2 Willapa Bay estuary tidelands and bathymetry (Clifton and Phillips 1980).

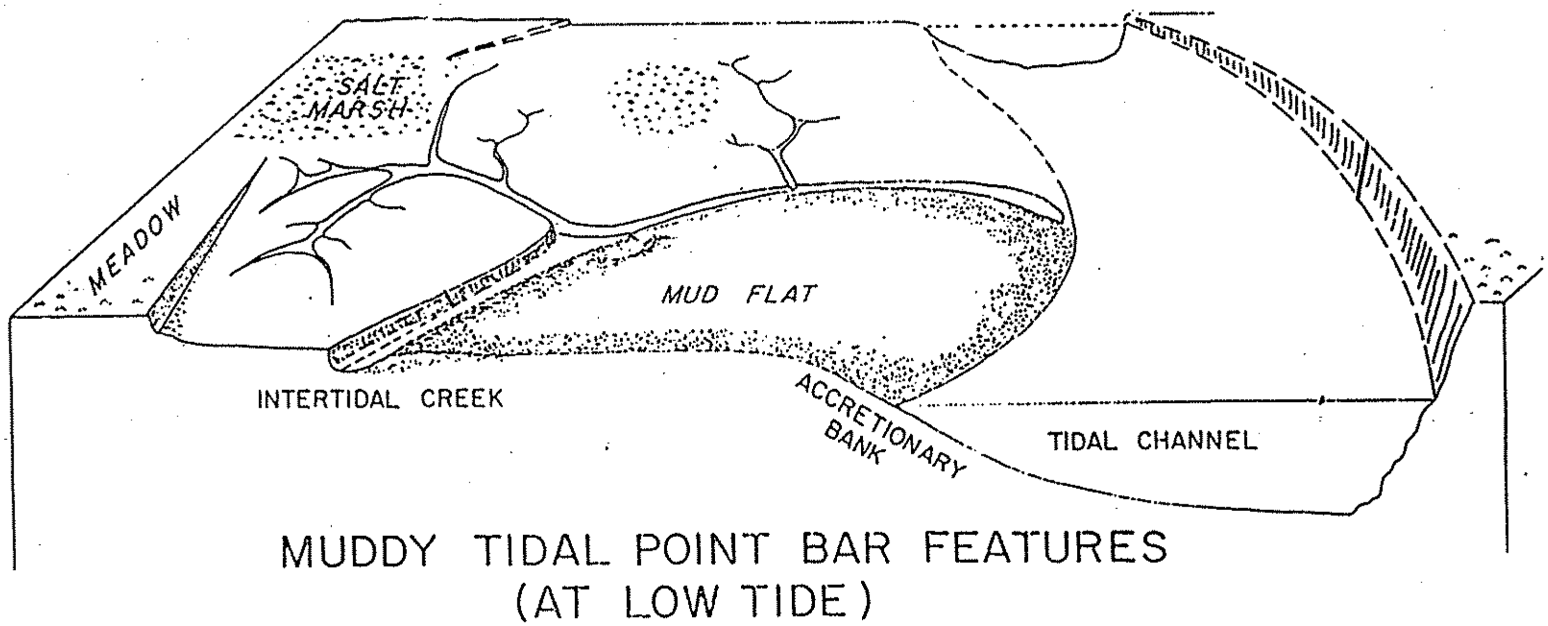


Figure 3.3 Diagram of estuarine tide flat features (Anima et al. 1989).

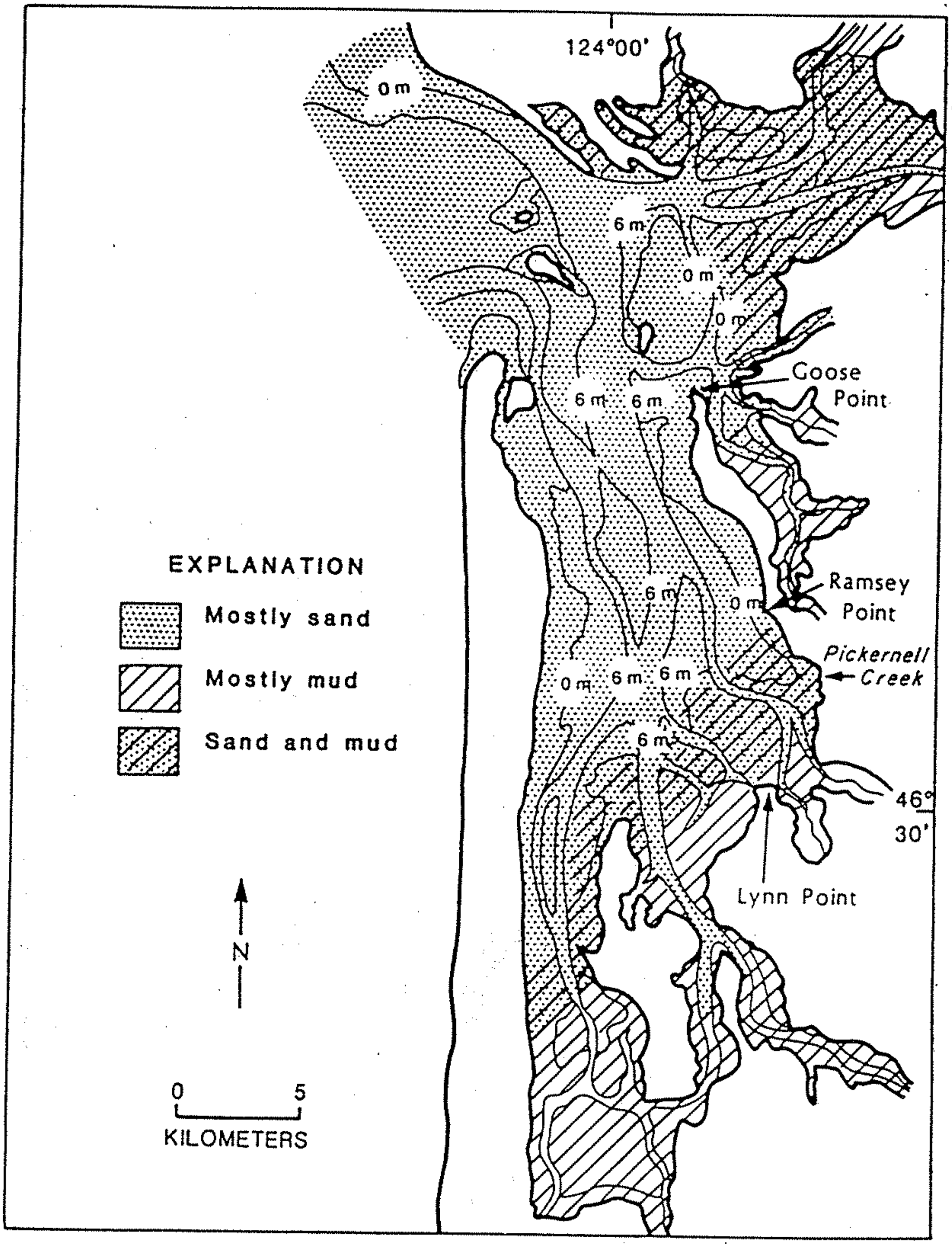


Figure 3.4 Sediment types within Willapa Bay. Depth contours at 0 m and 6 m refer to water depth relative to mean low water (adapted from Clifton 1983).

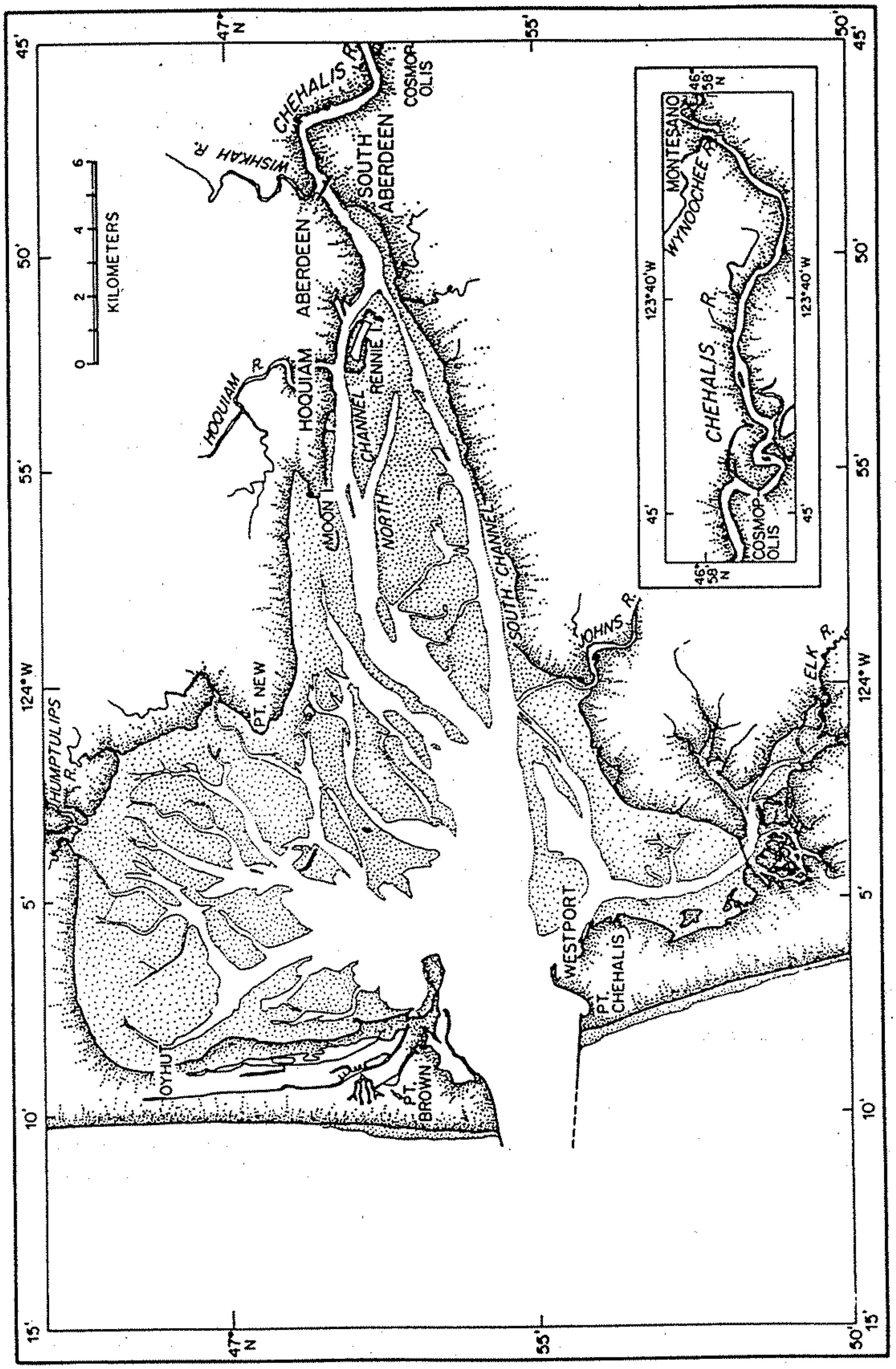
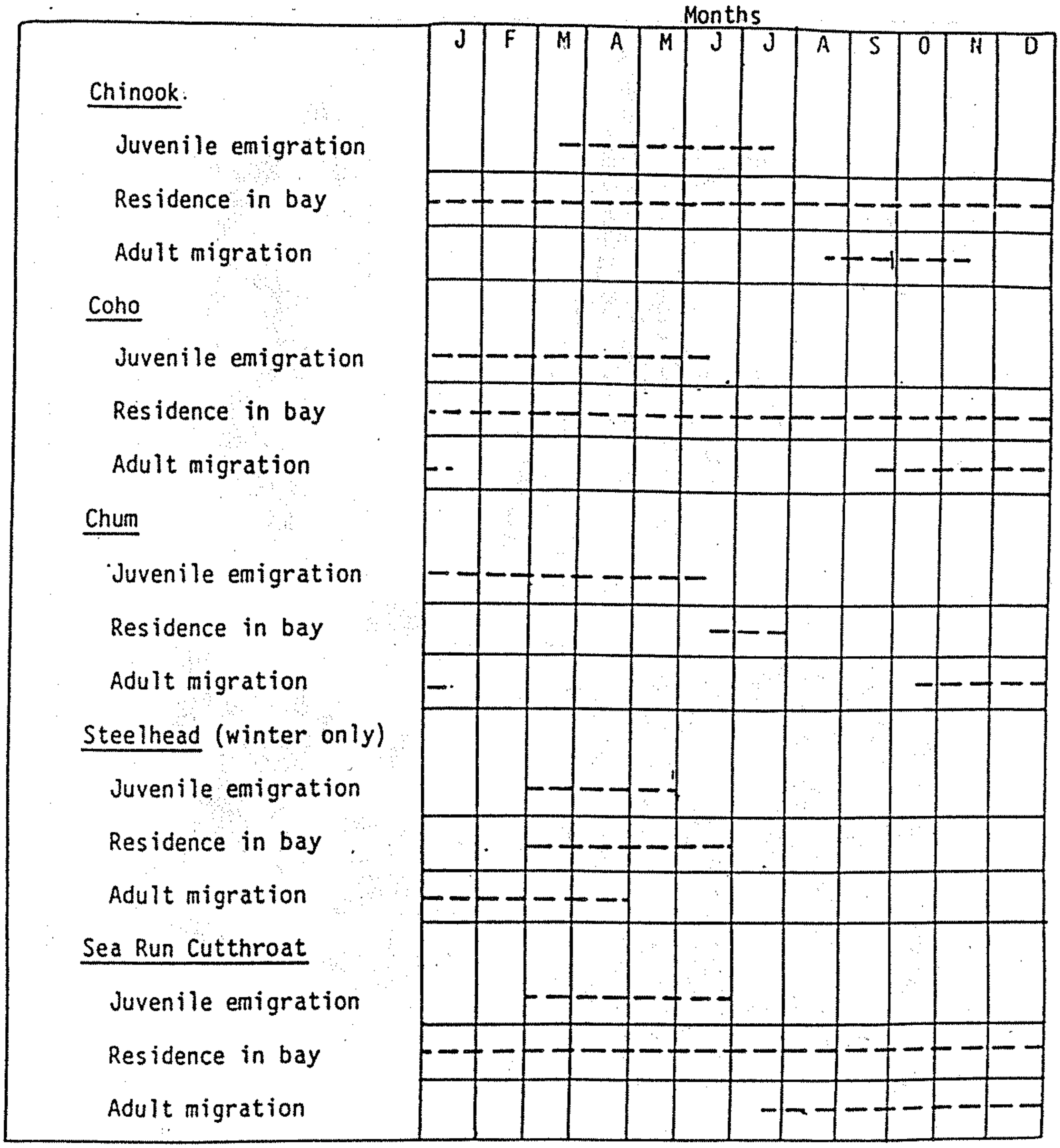


Figure 3.5 Map of Grays Harbor at MLLW showing extensive tidal flats (Loehr and Collias 1981)



Sources: USACE 1976 and Phinney and Bucknell 1975.

Figure 3.6 Timing of salmonid presence in Willapa Bay and tributaries (WDF/WDOE 1985).

4.0 ECOLOGY OF BURROWING SHRIMP

Two endemic species of burrowing shrimp (Decapoda, Thalassinidea) are considered pests to oyster farming operations in Willapa Bay and Grays Harbor. Both species are common in intertidal and shallow-subtidal sediments in Pacific northwest estuaries and both excavate sediment to construct tunnels and galleries beneath the sediment surface. Excavation and resuspension of sediments by the shrimp softens the substrate, buries oysters, and may interfere with oysters' filter feeding. Ghost shrimp (*Neotrypaea californiensis,* formerly *Callianassa californiensis*; Manning and Felder 1991) typically occupy sandier, well-sorted, intertidal and shallow subtidal sediments, whereas mud shrimp (*Upogebia pugettensis*) typically occupy muddier, fine-grained, intertidal and subtidal sediments. However, their distributions often overlap on mudflats and sandflats used for oyster farming. Hereafter, these species will be referred to as mud shrimp and ghost shrimp or by generic name only.

4.1 SPECIES DESCRIPTIONS

Ghost shrimp are characterized by a pinkish-tan body color, a large, broad abdomen, unequal-sized major chelae (claws on the first pair of walking legs), and a maximum adult length of ~9 cm (~3.5 in) (Fig. 4.1). The major chelae of females are slightly dissimilar in size, whereas those of males are very different in size. They are geographically distributed from Mutiny Bay, Alaska, to Estero Punta Banda, Baja California (Stevens 1928; MacGinitie 1934). Ghost shrimp create unlined tunnels and galleries that form complex, multi-branched burrow systems with multiple openings, and can extend 60 cm below the sediment surface (Stevens 1928; MacGinitie 1934; Swinbanks and Murray 1981; Swinbanks and Luternauer 1987). Excavated sediment and feces are deposited at burrow entrances, forming conspicuous mounds on the surface of the tidal flat. Ghost shrimp are generally regarded as sub-surface deposit feeders (MacGinitie 1934), although this has not been confirmed experimentally. Bird (1982) found that sediment organic content decreased in the presence of ghost shrimp, providing indirect support of deposit- feeding behavior. However, resuspension of sediment caused by their bioturbation and the resulting winnowing of fine-grained material could also cause a reduction of organic matter, and thus the trophic mode of ghost shrimp remains unresolved. Griffis and Chavez (1988) suggested that in the southern end of its range, ghost shrimp are generalists that deposit- and suspension-feed. They hypothesized that feeding mode and burrow morphology may vary with flow regime, sediment characteristics, and other environmental conditions that affect food supply. Nickell and Atkinson (1995) similarly noted that *Callianassa subterranea*, although primarily a sub-surface deposit feeder, can supplement its diet by suspension feeding.

Mud shrimp are characterized by a bluish-gray body color (with green and orange variants; WDF/WDOE 1985), major chelae of approximately equal size, and a maximum adult body length of ~13 cm (~5 in) (Fig. 4.1). The geographic distribution of mud shrimp ranges from Valdez Narrows, Alaska, to Morro Bay, California (MacGinitie 1930). Mud shrimp secrete a mucopolysaccaride to bind sediment particles and line their burrow walls. Their burrows are fairly permanent structures on tidal flats, particularly in comparison to ghost shrimp burrows. Mud shrimp generally are regarded as suspension feeders (MacGinitie 1930), and the "Y"- or "U"-shaped architecture of their burrows is consistent with those of suspension feeders that "pump" or move water mechanically (Griffis and Suchanek 1991). Although suspension feeding may be their primary source of nutrition, Stevens (1929) found some plant debris and fine sediment grains in the digestive tracts of mud shrimp, which suggests that they may also deposit feed. Evidence for trophic plasticity has been noted in other species of upogebiids. For example, Nickell and Atkinson (1995) found that *Upogebia stellata* is primarily a suspension feeder but has the ability to deposit and resuspension feed. As with ghost shrimp, burrows of *Upogebia* can extend 60 cm below the tidal flat surface and have multiple openings (Stevens 1928; MacGinitie 1930; Thompson 1972; Swinbanks and Murray 1981; Swinbanks and Luternauer 1987).

4.2 LIFE HISTORIES

The life histories of ghost shrimp and mud shrimp differ with respect to periods of reproduction and recruitment, stages of development, growth rate, and size at maturity (Bird 1982; Dumbauld et al. 1996). Both species become sexually mature at 2 to 3 years of age, and have been estimated to live 4 to 5 years (Bird 1982; Dumbauld et al. 1996).

4.2.1 Reproduction and Recruitment. Female ghost shrimp are ovigerous from April through August (Fig. 4.2). The eggs begin to hatch in June, and similar to mud shrimp, zoeae are released primarily during the night ebbs of neap tide series and exported to nearshore coastal waters (Johnson and Gonor 1982; Pimentel 1983). Ghost shrimp progress through five zoeal stages during their 6- to 8-week planktonic residence period (McCrow 1972) before postlarvae return to estuaries from August through October (Dumbauld et al. 1996). Washington coastal estuaries likely receive postlarvae that originate in other estuaries, transported by alongshore and cross-shelf, wind-driven surface currents (B. Dumbauld and K. Feldman, University of Washington, pers. comm.).

Mud shrimp are ovigerous from October through May (Fig. 4.2). The eggs, which are brooded on the female's pleopods, begin to hatch in March, and the zoeae are exported out of the estuary to the nearshore coastal ocean, typically during night ebb tides (B. Dumbauld and K. Feldman, University of Washington, unpubl. data). Zoeae spend 2 to 3 weeks in the plankton stage and progress through three zoeal stages (Hart 1937; Thompson 1972) before molting into postlarvae, which are capable of settling and assuming a benthic lifestyle. Recruitment to estuaries generally occurs from late April through June (Dumbauld et al. 1996).

After settlement has occurred, distinct cohorts of YOY ghost and mud shrimp are often detectable in size-frequency histograms (Dumbauld et al. 1996; Feldman et al. in press). The presence of several cohorts in Washington state is more likely caused by lengthy reproductive periods and asynchronous hatching of eggs, rather than by the production of multiple broods by single females (Dumbauld et al. 1996), although multiple broods have been noted in other thalassinid shrimps (Hailstone and Stephenson 1961; Devine 1966; Felder and Lovett 1989; Tamaki et al. 1996). Interannual postlarval recruitment densities are highly variable (Table 4.1) and are likely influenced by oceanic processes, similar to other decapod crustaceans with complex life cycles, such as the Dungeness crab, *Cancer magister* (McConnaughey et al. 1992). In Willapa Bay, Washington, YOY ghost shrimp densities exhibit temporal fluctuations in recruitment strength. For example, from 1992 to 1996, YOY shrimp densities at the Palix River ranged from a low of 0 YOY shrimp/m^2 to a high of 144 YOY shrimp/m^2 (Table 4.1; Fig. 4.3). Recruitment density also varies with respect to location within the estuary. In 1994, for example, mean density of YOY ghost shrimp at Goose Point (48 YOY shrimp/m^2) was approximately two times greater than that at Palix River (22 YOY shrimp/m^2), with densities at Nahcotta (13 and 30 YOY shrimp/m^2) falling in between the other two sites (Table 4.1; Fig. 4.3). Although larval transport and other processes may differ among sites, densities at different locations nevertheless exhibited similar interannual fluctuations (Table 4.1).

4.2.2 Growth and Maturity. Although postlarvae of both species of shrimp initially are about the same size, ranging from 0.9 mm to 1.4 mm carapace length (CL), which is measured from the tip of the rostrum to the posterior margin of the cardiac region of the carapace (K. Feldman, unpubl. data), mud shrimp grow faster and are larger than ghost shrimp of the same age. For example, mud shrimp grow rapidly their first summer, reaching 7 mm to 9 mm CL by August, just 4 months after settlement, whereas ghost shrimp do not reach this size for almost 2 years (Dumbauld et al. 1996). Dumbauld et al. (1996) found that, in Willapa Bay, Washington, mud shrimp grew an average of 4 mm to 5 mm CL/yr, whereas ghost shrimp grew 2 mm to 3 mm CL/yr, with males and earlier settling cohorts growing faster than females and later settling cohorts. Bird (1982) found that proximity to the mouth of the bay had a positive effect on growth rates of ghost shrimp, whereas conspecific density had a negative effect on growth. Hanekom and Erasmus (1988) similarly determined that *Upogebia africana* exhibited faster growth closer to the mouth of the estuary, but conspecific density had no effect on growth rates in that study. In addition to these factors, it is likely that trophic mode and seasonal timing of recruitment could contribute to differences in growth rates between species (Dumbauld et al. 1996). In Grays Harbor, Washington, estuarine water temperatures are 3°C to 6°C warmer in the summer than in the fall (Armstrong et al. 1991), which may partially account for the high rate of growth exhibited by YOY mud shrimp in the months following settlement relative to the rate of growth exhibited by YOY ghost shrimp.

Mud shrimp and ghost shrimp also differ in size, but not age, at maturity. Dumbauld et al. (1996) found that minimum size at oviposition was 22 mm CL for mud shrimp and 9 mm CL for ghost shrimp, although both species reached sexual maturity generally at age 3 in Washington. In Oregon, Bird (1982) estimated that shrimp attained maturity at age 2. With the onset of maturity, there is a corresponding change in the rate of growth of the carapace and segments of the major chela in males and females of each species (Dumbauld et al. 1996). Both species have been estimated to live 4 to 5 years (Bird 1982; Dumbauld et al. 1996), which is similar to other species of thalassinid shrimps found in temperate waters (Hailstone and Stephenson 1961; Devine 1966; Dworschak 1988; Rowden and Jones 1993).

4.3 EFFECTS ON OTHER BENTHIC ORGANISMS

Many studies have documented the reduction of species diversity and changes in the composition of benthic invertebrate communities in areas occupied by burrowing shrimp. Impacts to oyster are reviewed in Section 4.6; here we discuss their impacts to other species. At high densities, thalassinid shrimp are capable of influencing community composition by excluding species that are unable to withstand the disruption of sediment caused by burrowing and turnover of near-surface sediments (Peterson 1977; Branchlet 1981; Bird 1982; Murphy 1985; Posey 1986a; Posey et al. 1991; Dumbauld 1994; Tamaki 1994). Bioturbation associated with thalassinid shrimp may interfere with suspension feeding (Rhoads and Young 1970) and surface-deposit feeding (Tamaki 1988), bury newly settled larvae (Swinbanks and Luternauer 1987), and initiate small-scale emigrations (Tamaki 1988).

Negative effects of callianassid bioturbation also extend to seagrass communities. Suchanek (1983) found that productivity and percentage of cover of the turtle grass, *Thalassia testudinum*, were negatively correlated with the density of *Callianassa* spp. mounds. Significant deterioration of *Thalassia* transplants occurred in areas with high densities of *Callianassa* compared with control areas as a result of high turbidity or burial under sediment deposition. Ghost shrimp burrowing inside or adjacent to eelgrass (*Zostera* spp.) beds may cause unconsolidation of sediments around the roots and make the plants susceptible to up-rooting and wash-out during storms, although this has not been rigorously documented (R. Wilson and R. Thom, comm.). On the other hand, structurally complex root-rhizome mats associated with seagrass beds have been shown to reduce the mobility of several burrowing species (Branchlet 1982) and to limit the distribution of burrowers to areas outside these habitats (Ringold 1979; Harrison 1987; Swinbanks and Luternauer 1987). Branchlet (1982) found that mean burial time increased significantly for *Neotrypaea* in root-rhizome and animal tube mats compared with pre-burrowed bare sediments, and in the majority of laboratory trials, shrimp were unable to establish a burrow at all. Field surveys have been consistent with Branchlet's (1982) findings, noting the abrupt decline and low densities of *Neotrypaea* burrows in *Zostera marina* beds compared with adjacent intertidal mudflats (Swinbanks and Murray 1981; Swinbanks and Luternauer 1987). Harrison (1987) reported that an expansion of *Z. marina* and *Z. japonica* habitat was accompanied by a corresponding reduction in *Neotrypaea* density. Harrison (1987) suggested that in temperate geographic regions, cycles of eelgrass and shrimp activity are sufficiently out of phase to enable the rhizomes of eelgrass to expand in early spring before shrimp become too active. Other species of callianassids are restricted by root mats as well; Coleman and Poore (1980) noted a reduction in population densities of *Callianassa australiensis* and *C. limosa* in areas where *Zostera* was present. Dumbauld et al. (1997) present evidence that ghost shrimp restrict the distribution of *Z. japonica*, which expands aerially when shrimp are controlled with carbaryl. Thus, it is appears that ghost shrimp can affect the distribution of eelgrass beds and that mature eelgrass beds can inhibit the colonization of ghost shrimp.

In contrast to ghost shrimp, mud shrimp are able to penetrate through root and tube mats (Brenchley 1982) and, therefore, are not typically restricted from seagrass habitats. Dworschak (1987) noted that *Upogebia pusilla* burrows were more abundant in water-filled pools and *Zostera* patches than in elevated and unvegetated areas. In Brenchley's (1982) study, burrowing time increased with body size (indicating that small shrimp burrow better than large shrimp), suggesting that populations in dense root and tube mats may be skewed toward smaller mud shrimp.

Sediment turnover by thalassinid shrimps has been examined in several studies (e.g., Aller and Dodge 1974; Suchanek 1983; Branch and Pringle 1987; Witbaard and Duineveld 1989) although the lack of standardized methods to quantify rates makes comparisons between studies difficult (Rowden and Jones 1993). Turnover rates for ghost shrimp have been measured as 9 mL to 33 mL (wet sediment)/individual/day (Swinbanks and Luternauer 1987) and 1 m to 3 m (depth)/m/yr (Miller 1984). In contrast to the rates for ghost shrimp, reworking rates for mud shrimp are negligible (Swinbanks and Luternauer 1987; Dumbauld 1994), with sediment resuspension primarily occurring during burrow construction and enlargement (Posey et al. 1991).

As endemic species to intertidal and shallow-subtidal ecosystems, burrowing shrimp contribute to the flux of nutrients and materials between the water column and the sediment, create habitat for some benthic species, and are prey to fish and water birds (discussed later). The benefits of sediment reworking and burrow ventilation include nutrient recycling and greater oxygen penetration around the burrow wall (Koike and Mukai 1983). The physical structure of mounds and funnels that sometimes characterize shrimp burrows affect the benthic boundary layer flow and can induce flushing of water and ions, as can the currents created directly within burrows by shrimp fanning their pleopods (Allanson et al. 1992; Ziebis et al. 1996). The funnel can also act as a trap whereby detritus and other food particles may be deposited as a result of reduced shear stress associated with depressions. These biogenic structures also increase the surface area of the sediment available for colonization by bacteria and benthic microalgae (Branch and Pringle 1987), which may be important in promotive interactions on tidal flat communities. Dittmann (1996) found higher densities of meiofauna in the burrows of *Callianassa australiensis* than in sediments where the shrimp were excluded, perhaps caused by enhanced food supply. The burrows also are an important source of refuge for small fishes and crustaceans. In Washington, the arrow goby *Clevlandia ios*, the shore crab *Hemigrapsus oregonensis*, juvenile Dungeness crab *Cancer magister*, and the northern hooded shrimp *Betaeus harrimani*, occupy shrimp burrows on a temporary basis. These species, as well as the commensal bivalve, *Cryptomya californica*, may also benefit from the feeding current and food supply generated by the shrimp's pumping activities.

4.4 NATURAL PROCESSES THAT REGULATE SHRIMP ABUNDANCE AND DISTRIBUTION

4.4.1 Abiotic Factors. Species-specific distribution patterns are influenced in part by tolerance to physical factors such as anoxia. Swinbanks and Luternauer (1987) noted that on the Fraser River tidal flat in British Columbia, Canada, ghost shrimp were found up to the edge of the salt marsh (ca. + 0.9 m, up to 5 days maximum continuous exposure), whereas discrete beds of mud shrimp tended to occur no higher than mean sea level (ca. + 0.0 m, $\leq$ 0.5 days maximum continuous exposure). Dworschak (1987) noted that exposure time similarly limited the upper distribution of *Upogebia pusilla*. Dissolved oxygen concentrations are significantly lower in the burrows of thalassinid shrimps compared with the overlying water (Koike and Mukai 1983), and ventilation may be necessary at slack tides to promote the exchange of oxygen and waste products between the two environments (Allanson et al. 1992). At low tide, burrow waters are hypoxic, as well, and decline further with increasing exposure time (Thompson and Pritchard 1969b; Hill 1981).

In general, studies have found that upogebiids are less tolerant than callianassids to long periods of anoxia. Thompson and Pritchard (1969b) found that mud shrimp and ghost shrimp survive in anoxic conditions at least 3 days and have low metabolic rates based on laboratory studies conducted at 10°C. Mud shrimp, however, are less tolerant to anoxia and have higher metabolic rates than ghost shrimp. Mukai and Kioke (1984) similarly found that

Upogebia major has a lower tolerance to anoxia and a higher metabolic rate than *Callianassa japonica*. The morphology and function of the burrows may provide some basis for differences between species in their tolerance to anoxia. The unlined burrow walls characteristic of ghost shrimp are hypoxic, and at low tide, oxygen concentrations quickly equalize with those of interstitial waters (Torres et al. 1977). On the other hand, the well-lined burrows of mud shrimp offer greater insulation from hypoxic interstitial waters, and at low tide, oxygen levels are significantly higher in burrow waters than interstitial waters (Thompson and Prichard 1969b). Consequently, mud shrimp are not as physiologically tolerant to anoxia as ghost shrimp and, therefore, are restricted from occupying higher intertidal sites.

Burrowing shrimp, like other intertidal organisms, must also withstand environmental fluctuations in salinity, temperature, and desiccation. Mud shrimp and ghost shrimp are euryhaline species, capable of adapting to a wide range of salinities, but they differ in their physiological responses to salinity fluctuations. Mud shrimp are hyper-isosmotic regulators and are adept at regulating intracellular ionic concentrations, whereas ghost shrimp are osmo-conformers and poor ionic regulators (Thompson and Pritchard 1969a). Mud shrimp also have a lower lethal limit (3.5‰) than ghost shrimp (9‰ to 10‰), which may account for observations that mud shrimp can occur further up-estuary than ghost shrimp (Thompson and Pritchard 1969a). Similarly, Posey (1987a) found that significant mortality of ghost shrimp only occurred at salinities below 10‰. No mortality was observed at 10‰ to 33‰, although lowering the salinity reduced shrimp activity levels. Lower salinities and temperatures associated with winter may, therefore, contribute to the seasonal decline in burrow hole openings in winter months (Posey 1985, 1987a). Shrimp may also possess behavioral adaptations to resist water loss from tissues. Since water retention varies with sediment type, Griffis and Chavez (1988) hypothesized that shrimp inhabiting well-drained sandy sediments construct deeper burrows to maintain contact with water and thereby prevent desiccation during low tides. In muddier sediments, water levels change little and burrows may tend to be shallower.

Neither ghost shrimp nor mud shrimp are restricted to a particular sediment type; rather, both species are found in sediments ranging from fine muds to coarse sands and cobble. Bird (1982) determined that although sediment characteristics overlapped, mean particle size in mud shrimp colonies was finer than that from ghost shrimp colonies. Swinbanks and Luternauer (1987) found that the highest densities of mud shrimp occurred in muddy sands and sandy muds whereas the highest densities of ghost shrimp occurred in sandy sediments. In general, however, they could find no consistent correlation between textural properties of the sediment, such as percentage of mud content, median grain size and sub-sieve fraction, and burrow density of either species. Dworschak (1987) found that *Upogebia pusilla* burrows occurred in a wide range of sediment types as well. He noted that they seem to prefer muddy sands to muds, but again, there was no clear relationship between density and median grain size or sub-sieve fraction.

The presence of a relationship with sediment type may also be attributed to the shrimps' affects grain-size distributions. Callianassids tend to pump fine grains to the surface, whereas coarser particles are retained within the shrimp burrows (Suchanek 1983; Tudhope and Scoffin 1984; Wynberg and Branch 1994). Fine particles also are consumed during deposit feeding and redeposited in feces on the sediment surface (Witbaard and Duineveld 1989). Bioturbation may result in the deposition of alternating layers of fine and coarse sediments (Suchanek 1983) or, in intertidal areas swept by currents of sufficient velocity, feces and suspended particles can be transported off-site, resulting in a more homogeneous grain size distribution. Upogebiids, in contrast, do not significantly alter sediment structure, other than during burrow construction. Bird (1982) found that particle sizes were more variable (less sorted) in mud shrimp beds than in ghost shrimp beds. Wynberg and Branch (1994) similarly found that *Upogebia africana* did not appear to greatly modify the nature of sediment grain sizes, as opposed to *Callianassa kraussi*, which is sympatric with *U. africana*.

4.4.2 Biotic Factors. Although ghost shrimp and mud shrimp inhabit burrows that extend 60 cm into the sediment, they are vulnerable to predators because shrimp often are situated near the sediment-water interface. Posey (1985) observed that ghost shrimp spent over 25% of the time within 2 cm of the entrance to their burrows, often with part of their chela laying exposed on the sediment surface. Shrimp also have been observed crawling on the surface at low tide (K. Feldman, pers. obs.) as well as at high tide (Posey 1985). Whether related to feeding, ventilation, burrow maintenance, or mating, these behaviors expose burrowing shrimp to predation by epibenthic feeders.

One of the most common predators of burrowing shrimp in the Pacific Northwest is the staghorn sculpin, *Leptocottus armatus*. Staghorn sculpin are opportunistic, generalist predators common in estuaries along the west coast of North America (Hart 1974). Burrowing shrimp have been found in the stomachs of sculpin (Tasto 1975; Williams 1994) and comprise a substantial portion of their diet, particularly during summer months (Posey 1986b; Armstrong et al. 1995). Armstrong et al. (1995) found that combined ghost shrimp and mud shrimp comprised 70% of the diet of age 1 and older staghorn sculpin in July and 54% in August. Furthermore, staghorn sculpin have been shown to restrict the depth distribution of ghost shrimp (Posey 1986b). Sculpins were four times more abundant immediately seaward of a dense shrimp bed than over it, and when they were excluded from the lower intertidal, ghost shrimp successfully migrated down and survived (Posey 1986b). On a mudflat in Boundary Bay, British Columbia, Swinbanks and Murray (1981) similarly noted that ghost shrimp densities were highest in the mid-intertidal region and declined toward the lower intertidal and subtidal, perhaps caused by predation.

Other predators of burrowing shrimp identified by Posey (1985, 1986b) include cutthroat trout, (*Oncorhynchus carkii*, Dungeness crabs, *Cancer magister*, and Western gulls, *Larus occidentalis*. Although cutthroat trout preyed on ghost shrimp, they were rarely captured in beach seines over the 2-yr survey period, and thus were not likely to contribute substantially to shrimp population regulation in his study. Adult and juvenile Dungeness crabs were observed foraging over ghost shrimp beds, and in bare aquaria, attacked and consumed shrimp. Shrimp remains have also been reported in the stomachs of adult and subadult Dungeness crabs (Stevens et al. 1982). Posey (1985) noted the presence of ghost shrimp in the fecal pellets of Western gulls, suggesting that they occasionally prey on shrimp as well.

Although staghorn sculpin were the only predators of significance in Posey's (1986b) study, other predators, including those listed above, may play a greater role in shrimp population regulation in different habitats and estuaries. For example, starry flounder, *Platichthys stellatus*, are common in Coos Bay, Oregon, and they, as well other species of fish, may prey on shrimp subtidally (Posey 1985). Leopard sharks, *Triakis semifasciata*, common along the coasts California and Oregon, have been reported to prey on ghost shrimp and mud shrimp (Russo 1975), and there are anecdotal accounts of green and white sturgeon (*Acipenser medirostris*, *A. transmontanus*) predation on burrowing shrimp in the Pacific Northwest (B. Dumbauld, pers. comm.). Larvae of burrowing shrimp may also be an important seasonal prey item for water-column feeding fishes. Ghost shrimp larvae were found in the stomachs of Pacific herring (*Clupea pallasii*), chinook salmon (*Oncorhynchus tshawytscha*), and chum salmon (*O. keta*) captured in Tillamook Bay, Oregon, in June and July, and mud shrimp larvae were found in the stomachs of chinook salmon (Oregon Department of Fish and Wildlife 1977).

Finally, the gray whale, *Eschrichtius robustus*, has been observed to feed extensively on ghost shrimp. Gray whales migrate between calving lagoons in Mexico and Arctic feeding grounds (Rice and Wolman 1971), but some individuals enter Pacific Northwest estuaries to feed during the summer (Darling 1984). Weitcamp et al. (1992) documented between 2,700 and 3,300 feeding pits along 19 km of intertidal mudflats in Saratoga Passage, Puget Sound. They also reported seeing feeding pits in Willapa Bay. In Puget Sound, whales removed an average of 3 kg shrimp/pit, and ghost shrimp standing stock was approximately five times lower inside feeding pits than outside (Weitcamp et al. 1992). Although feeding opportunities were restricted to high tides, they estimated that whales in north Puget Sound could meet their daily energetic requirements in 16 to 170 min by feeding exclusively on ghost shrimp.

In addition to the effects of predators on shrimp abundance and distribution, a number of inter- and intraspecific interactions may further restrict the range and expansion of shrimp populations. Thalassinid shrimp have been the focus of several ecological "functional group" hypotheses that seek to understand how benthic communities are structured by grouping organisms according to how they modify the sedimentary environment. Among the most common hypotheses are those that classify organisms based on effects of adults on settling larvae (Woodin 1976), on the trophic mode of adults (Rhoads and Young 1970), or on the relative mobility of adults (Brenchley 1981, 1982). The concept of assigning species to discrete functional groups is an appealing approach to understanding community interactions; however, organisms do not always respond consistently to varying environmental conditions. Behavior, ontogeny, flow regime, and sediment transport all interact to create a unique set of conditions which affect benthic composition (Jumars and Nowell 1984). Nevertheless, there is some support for these hypotheses that may be helpful in understanding factors that influence shrimp distribution patterns and why populations of mud shrimp and ghost shrimp often are segregated.

Woodin (1976) suggested that species form discrete assemblages of 1) burrowing deposit feeders, 2) suspension feeding clams, and 3) tube builders. She proposed that each assemblage is maintained through negative interactions between established adults and larvae of other functional groups. Mobile deposit feeders (which burrowing shrimp might be classified as) are thought to inhibit sedentary suspension feeders and tube builders by disruption of the sediment and consumption of newly settled larvae during feeding. Suspension feeders reduce settlement of plankton by filtering larvae from the water column. Tube-dwellers reduce substrate availability, as well as prey and defecate upon larvae residing near or on the sediment surface. Several studies have examined interactions among these groups of organisms and concluded that adult benthos have an effect on recruitment success of other species as well as their own species (Breese and Phibbs 1972; Wilson 1980; Highsmith 1982).

With respect to burrowing shrimp, removal of ghost shrimp resulted in increased settlement of suspension-feeding bivalve larvae, *Sanguinolaria nuttallii* (Peterson 1977), and high densities of ghost shrimp have been correlated with low densities of tube-dwelling species (Posey 1985). Swinbanks and Luternauer (1987) suggested that distinct beds of ghost shrimp and mud shrimp could be maintained through interspecific interactions between adults and juveniles. They determined that a newly settled mud shrimp would have to completely reconstruct its burrow every 10 days to avoid burial under ghost shrimp mounds, which could increase the risk of mortality either through exposure to predators or increased energy expenditure. Moderate densities of adult mud shrimp, on the other hand, could reduce local recruitment of ghost shrimp by straining settling larvae from the water column. Given that both processes are highly localized, Swinbanks and Luternauer (1987) predicted that the two species of shrimp could coexist if population densities were not extremely high. In addition to interspecific interactions, adults can also facilitate recruitment of their own larvae by modifying the substrate to make it more hospitable (Thrush et al. 1992). Tamaki and Ingole (1993) found that *Callianassa japonica* larvae settle broadly, but post-settlement survival was higher in areas inhabited by adults, perhaps caused by greater ease of burrowing in, or oxygenation of, reworked sediments.

Although the results of many studies support the adult-larval functional group hypothesis, other studies have failed to demonstrate predictable inter- or intra-specific interactions between adults and larvae (Mauer 1983; Black and Peterson 1988; Commito and Boncavage 1989; Hines et al. 1989). Furthermore, other processes could produce patterns similar to those predicted by the adult-larval hypothesis, such as post-settlement predation (Luckenbach 1984), altered boundary layer flows around biogenic structures (Eckman 1983), and effects of organism activities on sediment stability (Brenchley 1981, 1982).

The trophic group amensalism hypothesis, developed by Rhoads and Young (1970), states that bioturbation by deposit feeders negatively affects suspension feeders. Resuspended particulates clog the feeding structures of suspension feeders, inhibiting their growth and survival. Rhoads and Young (1970) suggested that deposit feeders should be associated with fine sediments because of the greater surface area available for organic particle adhesion, thereby restricting suspension feeders to coarse sands with less turbidity. Murphy (1985) found that *Neotrypaea* produced sufficient turbidity while deposit feeding to negatively affect growth and survival of the suspension feeding bivalve, *Mercenaria mercenaria*. Surveys of subtidal transects of two adjacent sites revealed that these two species were spatially segregated. Murphy (1985) concluded that *Neotrypaea* restricted the distribution of *M. mercenaria*, whereas abiotic conditions prevented colonization of ghost shrimp in areas occupied by the bivalve. Similarly, Aller and Dodge (1974) determined that *Callianassa* sp. inhibited coral growth and settlement in a tropical lagoon in Jamaica. The negative impact of deposit feeders may be limited to subtidal areas characterized by slow currents, however, because there is no evidence to suggest that ghost shrimp have similar effects on suspension feeders inhabiting intertidal mudflats (Posey 1987b). Furthermore, a review of the literature reveals that members of a given trophic group rarely are associated with a particular sediment type, deposit feeders and suspension feeders often co-occur, and many species switch trophic modes in response to changing flow regimes (see review by Snelgrove and Butman 1994). These findings, which apply to mud shrimp and ghost shrimp, suggest that the trophic group amensalism hypothesis is not a broadly applicable explanation for species distributions.

Brenchley (1981, 1982) suggested that benthic community structure could be understood by examining effects of species' activities on sediment stability. Interactions between organisms of different mobilities would result in discrete distributions of species that tend to either destabilize or stabilize the sediment. Mobile infauna disturb the sediment by burrowing, depositing sediment grains on the surface, and resuspending particles in the water column. These disturbances bury sedentary species, disturb infaunal tube-dwellers, and disrupt the roots and rhizomes of seagrasses. In turn, the tubes and roots of sedentary species bind the substrate, which inhibits burrowing activities of mobile organisms.

Several studies have examined the effects of thalassinid shrimp bioturbation on sedentary and mobile infaunal species. Dumbauld (1994) found that species richness and diversity were significantly lower in a ghost shrimp colony than in a mud shrimp colony.

Moreover, the ghost shrimp bed consisted primarily of mobile species, whereas the mud shrimp bed consisted primarily of tube-dwelling and sedentary species. Ghost shrimp have been shown experimentally to have a negative effect on the abundance of sedentary infauna and a neutral or positive effect on mobile infauna (Posey 1986a). Tamaki (1988) found that *Callianassa japonica* had a positive effect on colonization by other mobile taxa, possibly by irrigating and fertilizing the sediment, which stimulated the growth of microalgae and bacteria, or by loosening up the sediment, which eased burrowing and penetration.

Reductions of burrowing shrimp mobility within seagrass beds were discussed in Section 4.5. Similar findings of reduced mobility have been reported in dense beds of tube-building polychaetes (Brenchley 1982) and phoronids (Ronan 1975). In both habitat types, the extent to which roots and tubes are capable of excluding burrowing organisms is a function of root or tube density, size and body morphology of the burrower, and degree of mobility (Brenchley 1982).

Although mobility-mode interactions can account for many species distributions, support for this hypothesis is based principally on studies in which large-bodied taxa have had negative effects on small organisms (see Posey 1990 and references therein). The strength of the interaction between functional groups is density-dependent as well as size-dependent. Moreover, it is difficult to categorize the effects of species as either stabilizing or destabilizing; sediment transport depends on interactions among flow, micro-topography, and species activities (Jumars and Nowell 1984). For example, animal tubes themselves are destabilizing biogenic structures, which may induce sediment erosion at any density (Eckman et al. 1981); however, tubes also enhance colonization by microbes, which tend to bind and stabilize the substrate (Eckman 1985). Even burrowing shrimp have contrasting effects on sediment stability: the mucous-lined burrow of mud shrimp stabilizes the substrate, but the expulsion of sediment during burrow construction results in destabilization. Posey et al. (1991) discovered that *Upogebia*, like *Neotrypaea*, negatively affected the abundance of several sedentary species, which was unexpected given the relative differences in burrow characteristics and mobilities between the two species of shrimp. In sum, although functional group hypotheses may only be applicable to specific habitats, organisms, and environmental conditions, they nevertheless have been instrumental in identifying potential mechanisms by which species interact, particularly with respect to thalassinid shrimp.

Finally, aggressive intra- and inter-specific interactions may be important in regulating the abundance and distribution of burrowing shrimp. Posey (1985) observed aggressive behaviors between ghost shrimp when burrow systems connected, until eventually one of the shrimp sealed off the intersection with sediment. YOY ghost shrimp also have been observed to seal points of intersection between burrow galleries (K. Feldman, pers. obs.). Aggressive behavior has been observed in mud shrimp as well. When given the opportunity to construct burrows in sediment-filled aquaria, many individuals fought instead, tearing the limbs and chelae off conspecifics (K. Feldman, pers. obs.). In contrast, ghost shrimp typically burrowed immediately into the sediment, avoiding unnecessary confrontations (K. Feldman, pers. obs.). Tunberg (1986) found that *Upogebia deltaura* kept in aquaria without sediment were aggressive towards each other as well, using their chelipeds to injure and kill each other. Damaged chelae and skewed sex ratios may further indicate that fighting is common in thalassinids (Felder and Lovett 1989; Dumbauld et al. 1996). Although aggressive intraspecific interactions may play a role in regulating shrimp densities, interspecific interactions may be involved in maintaining discrete populations of ghost shrimp and mud shrimp. Mud shrimp and ghost shrimp often occur together in mixed beds or in transition zones between single species beds, but tideflats with the highest densities of shrimp typically are populated by one species or the other. Interspecific interactions have not been well-documented, although Griffis (1988) has observed aggressive behavior among *Neotrypaea californiensis*, *N. gigas*, and *Upogebia macginitieorum*.

4.5 Recruitment into Live Oyster and Shell Habitats

Recruitment of YOY shrimp was quantified in one oyster bed in Grays Harbor containing areas in different stages of the production cycle and in an intertidal shell plot constructed by the U.S. Army Corps of Engineers (USACE) to enhance Dungeness crab settlement and survival. On the oyster bed, YOY ghost shrimp densities were significantly lower in an area with mature 3-year old oysters than in an area planted with oyster seed or in an untreated control (bare mud) area (Fig. 4.3A), suggesting that physical or biological attributes of the mature oyster bed inhibited shrimp recruitment success. Ground sprayed with carbaryl in July and left fallow was colonized by YOY ghost shrimp in the fall, and shrimp densities between the treated ground and an untreated control area were not significantly different (Fig. 4.3B), confirming the observation by Dumbauld (1994) that ghost shrimp postlarvae can colonize sprayed grounds immediately after carbaryl treatment. Because the physical structure of the habitat is unaffected by carbaryl spraying (with the notable exception of compaction of the substrate when adult burrowing shrimp are removed), we surmise that biological factors are responsible for inhibiting YOY ghost shrimp recruitment into beds containing mature oysters.

The USACE dredging-mitigation shell plot in Grays Harbor was also sampled to test whether a thick (10 cm to 15 cm) layer of epibenthic oyster shell applied to the mudflat would reduce recruitment of YOY ghost shrimp and mud shrimp. Four different configurations of shell and mud were sampled: 1) areas within the oyster shell plot covered 100% by epibenthic shell; 2) areas within the shell plot where oyster shell had sunk 5 cm to 10 cm below the sediment surface (sunken shell); 3) relic surface-shell deposits of eastern softshell clam, *Mya arenaria*, adjacent to the shell plot; and 4) bare mudflat. Surface shell reduced recruitment of ghost shrimp but not mud shrimp at the mitigation site (Feldman et al. in press; K. Feldman, unpubl. data). Densities of YOY ghost shrimp were lower in the epibenthic oyster shell and *M. arenaria* shell habitats than in sunken shell and bare mud (Fig. 4.4A). In contrast, densities of YOY mud shrimp were higher in the epibenthic oyster shell and *M. arenaria* deposits than in the sunken shell and bare mud habitats where ghost shrimp were prevalent (Fig. 4.4B).

Patterns of post-settlement densities at the USACE site may have been due in part to differential settlement or mortality of YOY shrimp in shell and mud habitats. Field experiments were conducted to identify settlement patterns in shell and mud substrates under natural tidal flows. Densities of ghost shrimp postlarvae were two to five times lower in epibenthic shell trays than in mud trays (Fig. 4.5). A similar but non-significant trend of lower settlement in shell was observed in a still-water habitat choice experiment in the laboratory (Feldman et al. in press). Results from an identical field experiment with mud shrimp postlarvae are not yet available, but in the laboratory experiment, a higher proportion of postlarvae settled in shell habitat, although the trend was not statistically significant (K. Feldman, unpubl. data).

Shrimp recruitment patterns also could have been modified by post-settlement predation. YOY Dungeness crabs occupy shell habitat at relatively high densities but rarely are found on unvegetated mudflats (Armstrong et al. 1992; Dumbauld et al. 1993). Thus, shrimp may be exposed to a higher risk of predation by this conspicuous predator in shell than mud habitat. Furthermore, ghost shrimp may be more vulnerable to crab predation than mud shrimp in shell because of differences in the seasonal timing of larval settlement. Ghost shrimp settle in late summer through fall when shell habitat is already occupied by large crabs at fairly high densities, whereas mud shrimp settle in spring, either ahead of a new Dungeness year class or when crabs are still very small and likely not significant predators of shrimp. In this sequence, mud shrimp may have a better chance to escape crab predation at settlement and opportunity to burrow and grow before crabs reach a larger, more predatory size.

Laboratory experiments examined predator-prey interactions between YOY Dungeness crabs and YOY shrimp to determine whether crabs forage on shrimp, quantify prey consumption per predator as a function of shrimp density, and determine the relative ranking of ghost shrimp in prey-choice experiments with other taxa common in epibenthic shell, e.g., gammarid amphipods, bivalves, polychaetes, and J1-instar Dungeness crabs (<9 mm carapace width, CW). YOY crabs successfully preyed on both YOY ghost shrimp and mud shrimp burrowed in shell habitat, but experiments were unable to detect an effect of shrimp density on proportional mortalities (Fig. 4.6 and 4.7). The lack of an increase in proportional mortality over the range of prey densities suggests that YOY crabs do not regulate shrimp populations. Nevertheless, results of prey-choice experiments with ghost shrimp revealed that ghost shrimp were the second most common prey item consumed by J2-instar (9.0 mm to 12.4 mm CW) and J4-instar (15.5 mm to 19.4 mm CW) crabs among those taxa listed above and accounted for the greatest amount of biomass (ash-free dry weight) in their diets (E. Visser, University of Washington, unpubl. data). In summary, although many other factors likely contributed to shrimp recruitment patterns, postlarval substrate selection was a determinant of initial ghost shrimp patterns and perhaps may be a determinant of mud shrimp patterns as well. Recruitment densities may be further modified by post-settlement mortality of YOY shrimp in shell caused by YOY Dungeness crab predation, but support from field experiments is needed to better assess the importance of this factor.

4.6 Measuring and Modeling Burrowing Shrimp Populations

4.6.1 Measuring Population Density. Three methods have been used to census the population density of burrowing shrimp. The first is the subjective "boot method" of testing the softness of the substrate (i.e., ability to hold weight) by pressing the sediment with their foot and observing the extent of topographic disturbance of the substrate created by the burrow openings and depositional mounds of burrowing shrimp. The concept is that as shrimp density increases, their burrowing and bioturbating liquify the sediment, which is discernable by the resistence of the substrate to pressure from one's foot. Furthermore, the abundance of burrow openings and mounds serves to confirm that the softness is related to the presence of burrowing shrimp. We could not find anyone who could articulate a consistent approach to using this method, nor how this method was used to distinguish shrimp infestation from one bed to another (or over time), nor how to account for features of the substrate (i.e., sediment type, presence of eelgrass or gravel) in the softness of the substrate. Oyster growers mainly use this method as a rule-of-thumb approach to judging the condition of their beds and may also use this approach to make decisions on whether to use physical control methods to mitigate shrimp impacts or to request formal site inspections for carbaryl treatment.

The second and most common quantitative approach has been to count the number of burrow openings on the sediment surface contained within a quadrat of fixed size (typically 0.25 m^2, 1 m^2, or 1 yd^2). The advantage to this method is the rapidity with which one can census the population density. This approach has three drawbacks, however: 1) the difficulty of differentiating burrows of the two shrimp species and of distinguishing shrimp burrows from those built by other benthic invertebrates, 2) the difficulty of corresponding burrow counts to the true number of shrimp living in the sediment, and 3) the difficulty in determining the size, age, or gender distribution of shrimp that formed the burrows.

The third census method is to collect sediment cores, sieve the sediment to recover the shrimp, and identify, count, and measure the animals. WDFW and University of Washington biologists use cores 40-cm diameter x 60-cm depth, and 3-mm mesh screens. The advantage of this method is that the maximum amount of information on the shrimp is available (species, gender, reproductive condition, age, length, abundance, etc.). The principal downfall of this method is the enormous labor required to collect and process each sample.

Since the 1960s, biologists have used burrow counts as a tool to assist decision making for the application of carbaryl pesticide to control burrowing shrimp (D. Tufts, pers. comm.). Oyster growers conduct burrow count surveys in March and April so that these data can be included in applications for permits to treat beds with carbaryl (D. Tufts, pers. comm.; L. Bennett, pers. obs.). The applications must be submitted in April to provide sufficient time for state regulators to process and issue permits in time for a mid-summer application of carbaryl. However, burrow counts taken in the winter and early spring (November through April) are poorly correlated with actual ghost shrimp or mud shrimp densities because of the relative inactivity of the shrimp during cold weather (Dumbauld 1994; Fig. 4.8 [bottom]). Burrow counts taken between May and October are better predictors of shrimp density for both shrimp species (Fig. 4.9), but the relationship between burrow number and shrimp density also varies spatially for ghost shrimp (Fig. 4.8 [top]) (Dumbauld 1994). Biologists were aware that pre-spray inspections of shrimp abundance on oyster beds conducted in the early spring resulted in an underestimate of the actual burrow count that occur when beds were sprayed (Tufts and Cooke 1983). They reported that burrow counts could increase four-fold as water temperatures increased during spring (47°F to 51°F). Thus, this memo (Tufts and Cooke 1983) implicitly acknowledged that the burrow count threshold was an underestimate of the true shrimp (and summer burrow count) density, and it also made the implicit assumption that early-spring burrow counts were predictive of burrow counts made later in the season. However, as we now know, burrow counts taken before May are poor predictors of actual burrowing shrimp density (Dumbauld 1994; Dumbauld et al. 1996). Likewise, burrow counts taken before May are poor predictors of burrow counts made between May and October because one cannot know in the winter-spring how many shrimp are present that will make burrows in the late spring-summer. Thus, the value of using early-spring burrow counts to predict the future abundance of burrowing shrimp, let alone the damage they may inflict on oysters, is highly suspect.

To obtain more accurate estimates of the true density of burrowing shrimp populations, oyster growers must change their monitoring practices. This is not to suggest that sediment cores should be taken, although that approach would provide the best quality information. Burrow counts taken later in the season (such as after mid-May, but before mid-October) would yield more accurate population estimates. However, as was shown in Figure 4.9 (top), the burrow-count-to-shrimp relationship can vary with location (possibly caused by differences in substrate, exposure to currents and moving sediment, tidal elevation, or other environmental factors), and oyster growers will need to evaluate the accuracy of burrow counts for oyster beds in different locations within the estuary.

New methods should be developed to rapidly and accurately census the burrowing shrimp and their potential to cause damage to oysters. One approach to investigate is an index that combines information on shrimp density (i.e., burrow counts), the softness of the substrate (i.e., sediment shear strength and penetrability), and features of the substrate (i.e., sediment type, density of eelgrass). Such an index would thus integrate indicators of the abundance of the shrimp, the innate ability of the sediment to support oysters, and the effect of burrowing shrimp on the geophysical properties of the sediment. This index, or any other new census method, would have to be verified as accurately measuring shrimp abundance and/or the risk of shrimp damage to oyster yield.

Methods are also needed to monitor rates of shrimp recruitment into individual oyster beds. Recruitment rates vary annually and spatially within the estuaries, and information on recruitment onto specific beds will help growers and biologists predict the abundance of burrowing shrimp in the following year. These data would be particularly valuable if they were used in conjunction with population growth models.

4.6.2 Modeling Population Dynamics. Estimates of shrimp population growth rates would benefit efforts to manage burrowing shrimp by providing a method to predict the likely densities of shrimp. It may be possible to make such predictions of population densities 1 yr or 2 yr distant. We summarize here two efforts at estimating population parameters that will assist the development of population growth models. One approach is to estimate net population growth rate based on historical data sets containing time series of burrow-count or shrimp density data. The other approach is to estimate rates of mortality for males and females of different size classes of ghost shrimp. These data could eventually be used to develop a demographic model for this species.

4.6.3 Net Population Growth Rate Estimates. We could find no published data on rates of population growth for either ghost or mud shrimp. We analyzed two data sets containing sequentially collected burrow count or total shrimp density data. The first was the WDFW burrow-count data set, containing records from site inspections prior to issuance of spray permits, dating from 1963. These data were sorted for sites having sequential burrow-count data. The second data set was provided by Dr. Brett Dumbauld (WDFW), containing both burrow-count and actual shrimp density data for both species, collected at sites near the mouth of the Palix River (ghost shrimp) and near the mouth of the Cedar River (mud shrimp) in Willapa Bay. Net annual population growth rates were estimated as the difference in counts between censuses, divided by the number of years between censuses.

Results of analyses for the two data sets are summarized in Tables 4.2 and 4.3. The net rate of population growth based on burrow counts was positive for both species in both data sets. However, the population monitored by Dumbauld showed substantially higher growth rates than those contained in the WDFW data set (i.e., six-fold higher growth rate for ghost shrimp burrows, and two-fold higher growth rate for mud shrimp). Furthermore, the variability in population growth rate estimates was much greater for populations monitored by Dumbauld (Coefficient of Variation [CV] >100%) than for those contained in the WDFW data set (CV <90%). These differences probably resulted from the low densities of burrows typically found in early-spring censuses (WDFW data set) as compared with the higher densities of burrows found in warmer seasons (Dumbauld data set). Furthermore, the ghost shrimp and mud shrimp populations represented in Dumbauld's data set experienced a decrease in density in 1991, whereas little change in population size was observed from 1993 to 1994. These events would serve to increase the variability in the population growth rates in the Dumbauld data set. In contrast, for many of the sites included in the WDFW data set, censuses were not taken every year, so annual fluctuations in population size would tend to be filtered out, thus reducing the variability in population growth rate.

It is interesting to note that Dumbauld's data set comes from dense populations of shrimp that had not been treated with carbaryl, whereas many of the sites in the WDFW data set had been sprayed with carbaryl at least once in their past. In addition, many of the sites censussed by WDFW had oysters growing on the substrate, and their presence could have inhibited recruitment, affected the construction of burrow openings by the shrimp, or interfered with burrow counting. One might expect the populations censussed by WDFW to have undergone rapid rates of population growth in recently defaunated habitat, whereas the populations monitored by Dumbauld might be expected to have reduced rates of population growth because the shrimp were already present at high density (the burrow densities in 1989 were 260 b/m^2 and 163 b/m^2 for ghost and mud shrimp, respectively). Again, the discrepancy between expectation and observation may have been caused by the inaccurate estimates of the true population sizes of burrowing shrimp in the WDFW data set.

It is also important to note that variation in population growth rate was lower for censuses based on actual shrimp counts than for censuses based on burrow counts (Dumbauld data set). This provides further evidence that burrow-count data are much less reliable than direct counts of individuals as a means of measuring population size.

In summary, it is premature to base a population growth model based on burrow-count data using information from these two data sets. The WDFW data set, although large, is inappropriate for population modeling because the burrow-count data were all collected in early spring when the shrimp were inactive. Furthermore, Brett Dumbauld's data set demonstrated that population growth estimates based on burrow counts were much more variable than estimates based on counting the actual shrimp. At present, there is insufficient information to build a population growth model without obtaining additional data sets. Population census data should be obtained from a variety of locations in order to measure the variability in population growth rates that might occur in different habitats within Willapa Bay and Grays Harbor.

4.6.4 Mortality Estimates. There is no published information on rates of natural mortality for either ghost or mud shrimp. We analyzed gender-specific abundance and length-frequency data for ghost shrimp that had recruited onto experimental plots in Palix River in the months and years following carbaryl treatment. Using a simple exponential growth model, Feldman and Dumbauld (unpubl. data) estimated net mortality rates (Z) for males belonging to the 1989 year class as 1.17/yr from 1990 to 1991, 1.64/yr from 1991 to 1992, and 1.41/yr, spanning a 2-yr period from 1990 to 1992 (Table 4.4). Three modes (cohorts) of 1+ males (4.1, 5.4, and 7.5 mm CL) totaling 100 individuals were identified in 1990 using MIX (Table 4.5, Fig. 4.10). In 1991, two modes of 2+ shrimp (8.7 and 11.2 mm CL) totaling 31 individuals were apparent, and in 1992, one mode of 3+ shrimp (15.6 mm CL) totaling 6 individuals was identified (Table 4.5, Fig. 4.10).

Correctly assigning each age classes to the appropriate carapace length is critical to estimating mortality. If, for example, the 7.5 mm CL component in 1990 actually represented 2+ shrimp (not 1+ shrimp), then an estimate of mortality would be much lower [51 (1+) shrimp → 31 (2+) shrimp → 6 (3+) shrimp, instead of 100 → 31 → 6. It is possible that some of the males in the 7.5-mm mean CL component were actually 2+ individuals, but the MIX program was unable to converge on another modal peak caused by low sample size. However, given the available data, information on sex-specific growth rates (Dumbauld et al. 1996), and the potential for faster growth as a result of reduced competition (caused by removal of older age classes), we suggest that the 7.5-mm-CL shrimp are most likely 1+.

Estimates of Z for females belonging to the 1989 year class are 1.54/yr from 1990 to 1991, -1.06/yr from 1991 to 1992, and 0.24/yr spanning a 2-yr period from 1990 to 1992 (Table 4.4). Although the slope of the regression curve over 1990 to 1992 was lower for females than that for males, the statistical fit was also much poorer (r^2 = 9% for females and 99% for males; Table 4.4). Two modes (cohorts) of 1+ females (5.1 and 6.8 mm CL) totaling 182 individuals were identified in 1990 using MIX (Table 4.6, Fig. 4.10). In 1991, one mode of

2+ females (9.3 mm CL) totaling 39 individuals was apparent, and in 1992, one mode of 3+ shrimp (10.8 mm CL) totaling 113 individuals was identified (Table 4.6, Fig. 4.10). It is unclear whether the low number of 2+ shrimp in 1991 was the result of sampling artifacts or whether the net effect of mortality, emigration, and immigration accounted for the progression of 182 shrimp in 1990 to 39 in 1991 to 113 in 1992. The presence of older (3+) females in 1991 (11.8 mm CL; Table 4.6, Fig. 4.10), however, is suggestive of movement of shrimp into plots. If instead these older individuals had been present in plots in 1989 and survived carbaryl treatment, then some of these females should have shown up in length-frequency histograms as 2+ shrimp in 1990.

Based on the Z values calculated above, the abundance of male ghost shrimp within a given year-class might decline 75%/yr on average so that a bed with 100 (1+) males/m^2 would decline to 25 (2+) males/m^2 one year later to 6 (3+) males/m^2 two years later. Similarly, the abundance of female ghost shrimp within a given year-class might decline 22%/yr on average so that a bed with 100 (1+) females/m^2 would decline to 78 (2+) females/m^2 one year later to 61 (3+) females/m^2 two years later. In sum, the Z values derived for ghost shrimp mortality should be considered "ball park" figures, not accurate estimators of true mortality. Error and uncertainty are inherent in these values in part because estimates were derived from a single experiment with low sample size, a single location, and over one time period. Conspecific density, interannual fluctuations in environmental conditions, natural disturbance, predation pressure, and other site characteristics are key factors that should be recognized and quantified, if possible, when calculating mortality estimates. It is also important to understand other processes that regulate shrimp population structure, such as growth rates and movement patterns, which may mask trends in mortality. Growth rates differ between sexes and cohorts (Dumbauld et al. 1996) and vary with conspecific density and food supply (Bird 1982), which make age determinations difficult. There is some evidence of movement by shrimp (Posey 1985; Feldman et al. in press), either through active choice or bedload transport, that further obscures mortality estimates. Finally, mortality rates may differ for mud shrimp populations based on differences in life history and behavior between the two species. We focused on ghost shrimp in this exercise because they pose a greater overall threat to oyster production, and the data set was more conducive to analysis than that from a similar experiment conducted by Dumbauld (1994) on mud shrimp. Additional experiments and a greater understanding of shrimp life history therefore are needed in order to derive better estimates of natural mortality for burrowing shrimp.

4.6.5. Demographic Population Model. A population model to forecast future densities of each species and the possible damage from shrimp populations would have to be based on more than net population growth or net mortality. To be most useful, the model would have to be species-specific, have the capability to generate site-specific forecasts, and be able to predict the relative abundance of damage-causing and innocuous size classes (i.e., 1+ and YOY, respectively). Demographic models, such as stage-matrix models described by Caswell (1989), offer these capabilties. Information needed to construct these models is age- or size-specific mortality, growth, lateral immigration rates, and recruitment rates. A preliminary model could be constructed using vital rates reported in this paper (i.e., mortality and recruitment) and data from simple field studies. Using this model, sensitivity analysis can be conducted to determine which vital rates have the greatest impact on population growth-rate estimates. This would point out which data need to be monitored most precisely on a site-specific basis to generate predictions about shrimp populations on that site. Recruitment rate, current population size, and the age- or size- distribution of the shrimp are most likely to be the data needed to develop site-specific population models.

4.7 IMPACTS OF BURROWING SHRIMP ON OYSTER FARMING

Oyster growers report that burrowing shrimp abundances within Willapa Bay and Grays Harbor have increased dramatically since the 1950s. Furthermore, they report that the geographic distribution of the shrimp in the estuaries has expanded, most notably toward the mouths of tributaries. To our knowledge, these observations have not been substantiated by reports or other records of burrowing shrimp abundance and distribution prior to and during that period, but this story is part of the oral history of oyster growers and other long-time residents of the area (interviews with oyster growers; Clyde Sayce, pers. comm.). Old photographs show people standing on top of firm sediment in oyster beds that are presently too unconsolidated to support a person on foot (C. Sayce, pers. comm.). Regardless of incontrovertible evidence of a burrowing shrimp population explosion, the productivity of the oyster industry in Willapa Bay and Grays Harbor began to decline after the mid-1940s. Oyster growers started experimenting with shrimp control methods in the 1950s (L. Weigart and D. Tufts, pers. comm.) and started using carbaryl to control burrowing shrimp in 1963 (WDF/WDOE 1985).

The underlying reasons for the expansion of burrowing shrimp populations is not known. High densities of burrowing shrimp are found in other estuaries, including Tillamook Bay, Yaquina Bay, and Coos Bay, Oregon, and it is possible that a common causal mechanism is responsible. If so, the cause could either be of broad geographic distribution (i.e., climatic conditions or loss of widely dispersing predators) or repetition of some action in all places (i.e., a human impact on the estuaries). Many of those we interviewed also suggested that reductions in finfish populations (particularly salmonids and sturgeon) have resulted in a decrease in predation pressure on burrowing shrimp populations. As noted above, staghorn sculpin and Dungeness crabs are important shrimp predators and can regulate the burrowing shrimp populations, but it is not clear whether salmonids or sturgeon actually affect the abundance of larval or benthic shrimp. Others have suggested that disturbance of sediments and benthic communities caused by oyster farming might enhance the susceptibility of oyster beds to invasion by burrowing shrimp (Simenstad and Fresh 1995). If this were the dominant process, it is unclear why high shrimp densities have persisted in areas where oyster farming has been sharply curtailed (e.g., Tillamook Bay, Oregon; Ken Brooks, pers. comm.) or has not occurred at all in other areas (e.g., lower Yaquina Bay, Oregon; T. DeWitt, pers. obs.). Alternatively, grain-size properties of sediments may have changed on tide flats in the estuaries as a result of deposition of eroded upland soils, which may have created habitat conditions favorable to ghost shrimp or mud shrimp.

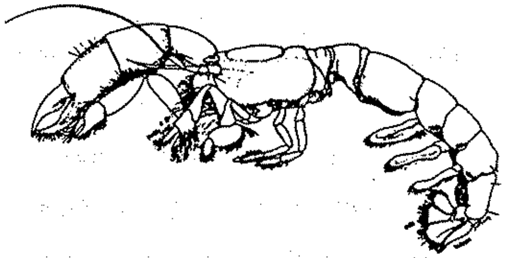
Several growers and other experts whom we interviewed suggested that El Niño oceanographic and climatic patterns, resulting in warmer ocean temperatures or reduced rainfall, were responsible for changes in burrowing shrimp abundance. Increased water temperatures might enhance somatic growth rates, which could bring burrowing shrimp to sexual maturity more rapidly and would cause population growth rate to increase. The expansion of burrowing shrimp populations (particularly ghost shrimp) toward the confluence of tributaries suggests either an increase in the shrimp's tolerance to low salinity or a change in the salinity dynamics within the estuaries. In particular, the advent of flood control practices (particularly dams and regulation of water-release rates) and changes in rainfall patterns could reduce the frequency or magnitude of very low-salinity events within the estuary (Ebbesmeyer and Strickland 1995). As neither species of burrowing shrimp can tolerate salinities below 3‰ (Thompson and Pritchard 1969a; 10‰ for ghost shrimp, Posey 1987a), low salinity may have contributed to regulating the distribution and abundance of ghost and mud shrimp. In any event, the lack of knowledge about the causes of burrowing shrimp population expansion may ultimately limit efforts of controlling their impacts to oyster farming to temporary, prophylactic solutions, such as chemical or physical control measures.

4.7.1 Mechanisms of Adverse Impacts to Oysters. Survival and growth of the Pacific oyster, *Crassostrea gigas*, and many other benthic organisms are negatively affected by the bioturbating activities of burrowing shrimp. Shrimp burrow construction and, possibly, feeding activities result in rapid turnover of sediments, deposition of sediment on the tidal flat surface, resuspension of sediment, modification of sediment grain-size distribution, reduced sediment compaction, and increased water content in the sediment (Stevens 1929; Loosanoff and Tommers 1948; WDFW 1970; Simenstad and Fresh 1995). Sessile organisms, such as oysters, may be buried by deposited sediment or sink into the softened, unconsolidated substrate. Additionally, resuspended sediments can interfere with feeding activities of suspension feeders, such as oysters, by clogging the filtering and food transport organs (e.g., gills and ciliary tracts).

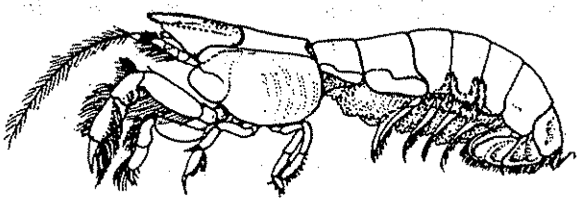
Most oyster growers reported during formal and informal interviews that ghost shrimp cause more damage to oyster crops than do mud shrimp. Some longline growers reported that they could tolerate moderately high densities of mud shrimp on their oyster beds without experiencing serious economic harm, although what that density is could not be quantified. As discussed previously, sediment deposition rates are higher in ghost shrimp beds than in mud shrimp beds (see also Dumbauld 1994), which suggests that rates of oyster burial would be greater on ghost shrimp beds. Finally, Dumbauld (1994) found that survival of seed oysters was higher on beds dominated by mud shrimp than on beds dominated by ghost shrimp. Thus, in addition to differences in their life histories and habitat requirements, these two species of burrowing shrimp differ in their effects on oysters. These differences should be taken into consideration when developing critical control thresholds and control tactics.

Some oyster growers and estuarine scientists that we interviewed speculated that oysters and burrowing shrimp, particularly mud shrimp, compete for food (i.e., phytoplankton and resuspended benthic microalgae). Such competition should be manifested by reduction in oyster growth or condition in the presence of high densities of burrowing shrimp. However, Dumbauld (1994) did not observe significant differences in meat weight, shell size, or condition index for oysters in the presence or absence of either mud shrimp or ghost shrimp up to three years after carbaryl spraying to eradicate shrimp from 100 m^2 treated plots and 15 m wide strips. Thus, on a small to medium scale (< 3 ha), there does not appear to be support for the food competition hypothesis. However, it is not known whether food competition between burrowing shrimp and oysters (and other suspension feeders) occurs on an estuary-wide scale. Large-scale competition between suspension feeders has been reported elsewhere (Black and Peterson 1988), and it is conceivable that the high densities of burrowing shrimp within Willapa Bay and Grays Harbor significantly reduce the availability of food for oysters.

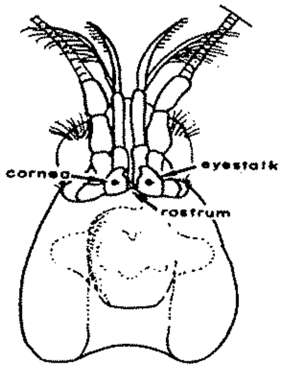
4.7.2 Beneficial Aspects of Burrowing Shrimp to Oyster Farming. Although notorious for their adverse impacts to oysters, burrowing shrimp can also benefit commercial oyster farming. As noted above, by pumping large volumes of water through their burrows, burrowing shrimp can significantly affect the flux of nutrients and particulate matter between the sediment and overlying water. Most likely, there is a net flux of nutrients out of the sediment (Koike and Mukai 1983), which could help stimulate primary productivity in the overlying water, thereby enhancing the food supply of oysters. This would only be significant if oysters were food-limited and if primary productivity was nutrient-limited. Secondly, burrowing shrimp help protect oyster beds from trespassers and poachers by making the tide flats impassable to foot traffic between the shoreline and oyster beds. Although growers do not enhance shrimp densities in order to produce a protective barrier, some do deliberately avoid killing shrimp on ground that serves that purpose (L. Bennett, pers. obs.).



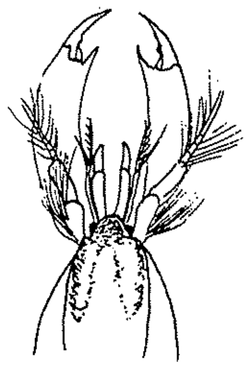
Ghost shrimp (*Neotrypaea californiensis*)
adult male, 5 cm length



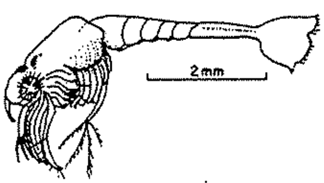
Mud shrimp (*Upogebia pugethusis*)
gravid female, 9 cm length



Ghost shrimp head



Mud shrimp head



Mud shrimp larva

Figure 4.1 Illustrations of ghost shrimp and mud shrimp (adapted from Rudy and Rudy 1983).

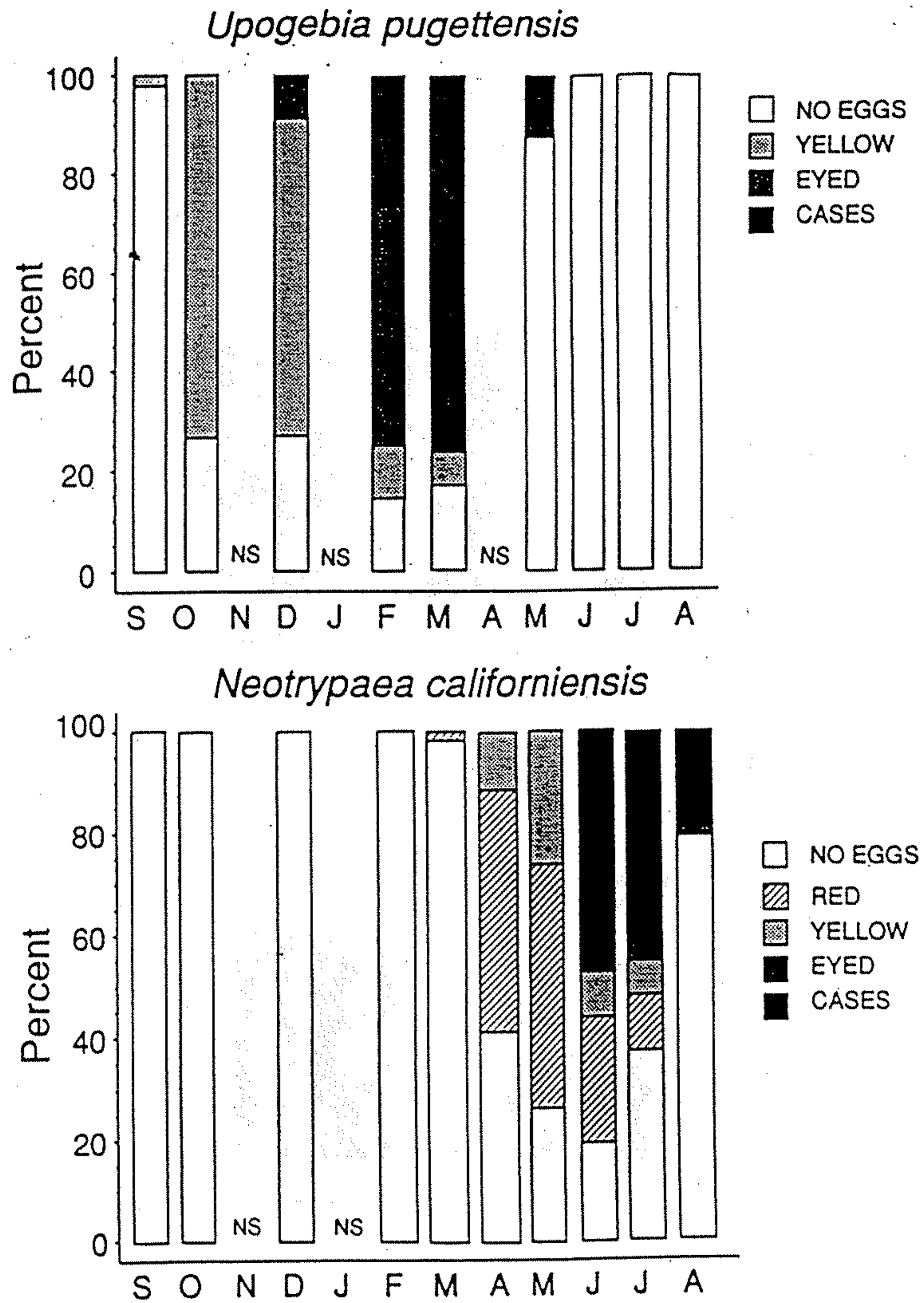


Figure 4.2 Seasonal presence of ovigerous female burrowing shrimp, *Upogebia* (Top) and *Neotrypaea* (Bottom), with eggs in various stages of development from newly extruded red eggs in *Neotrypaea* and yellow eggs in *Upogebia* to eyed eggs and finally empty egg cases found on the pleopods after hatch for each species. Note difference in seasonal timing of reproductive cycle between species. NS = no samples were taken. (Dumbauld 1994).

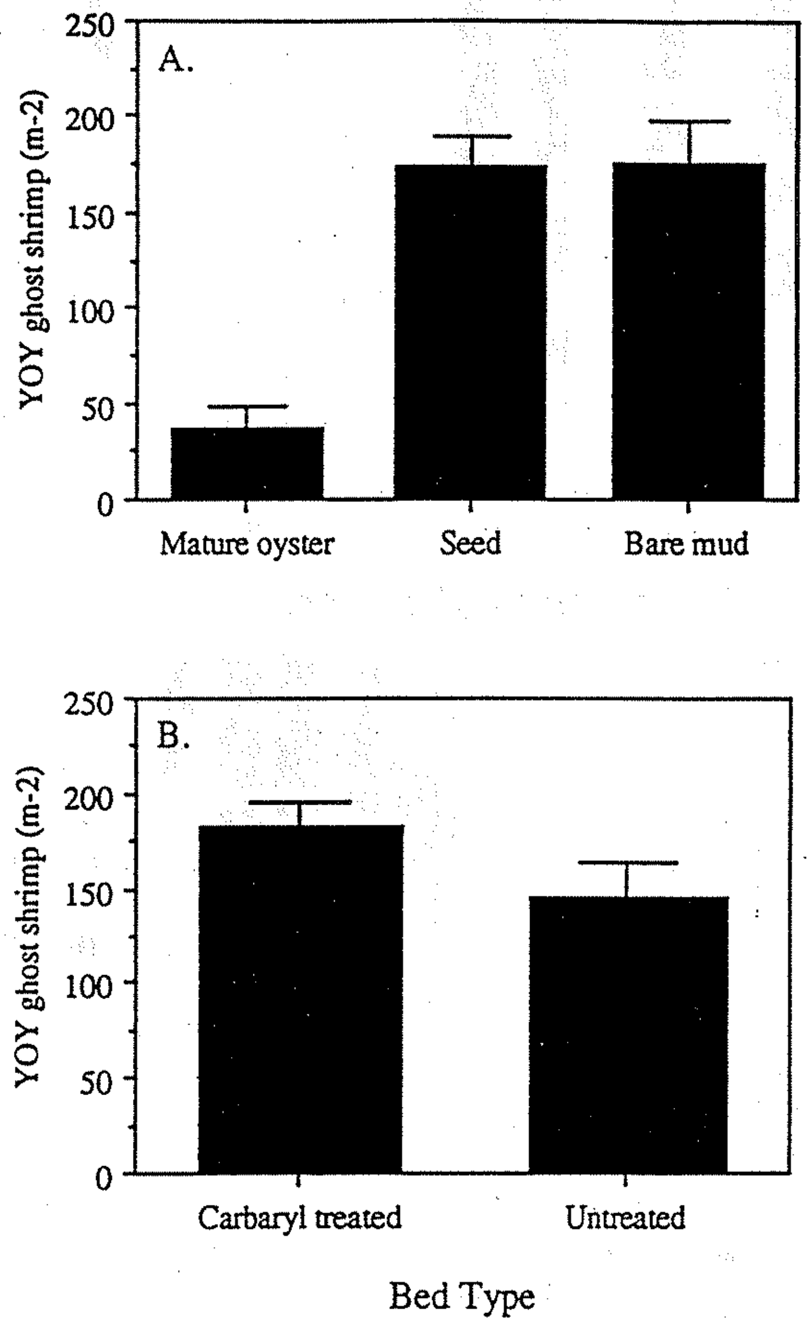


Figure 4.3 Mean densities of Young-of-the-Year (YOY) ghost shrimp (shrimp/m^2; ±1 SE) on (A) areas of an oyster bed in South Bay, Grays Harbor, in different stages of the oyster production cycle and (B) ground treated with carbaryl 5 months prior to sampling versus untreated bare mud (K. Feldman, B. Dumbauld, and D. Armstrong, unpubl. data).

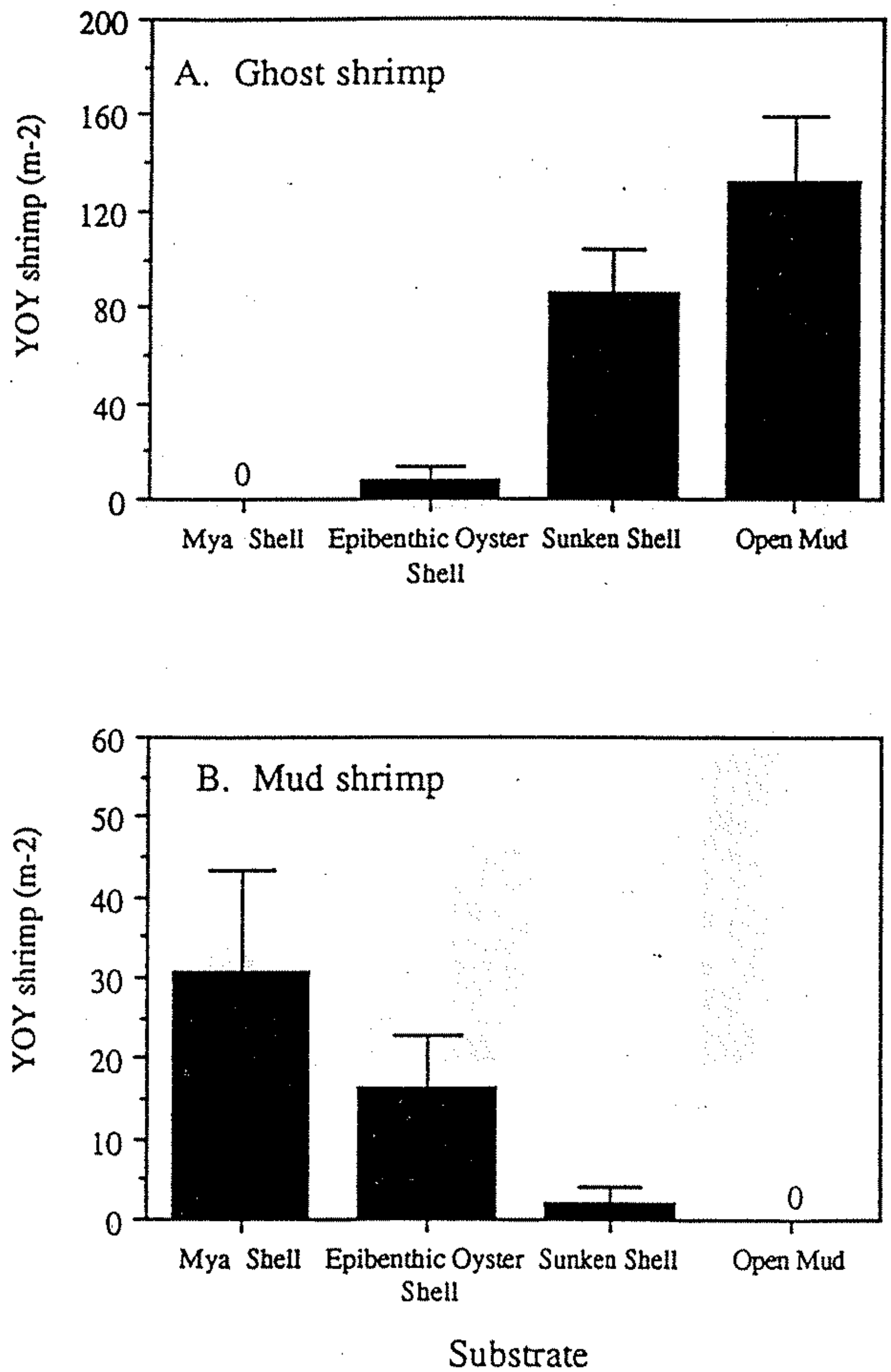


Figure 4.4 Mean densities of YOY (A) ghost shrimp and (B) mud shrimp (shrimp/m^2; ±1 SE) in various shell and mud substrates at Pacman, the site of a USACE mitigation shell plot in Grays Harbor, Washington. Samples were collected June 1993 (K. Feldman, B. Dumbauld, and D. Armstrong, unpubl. data).

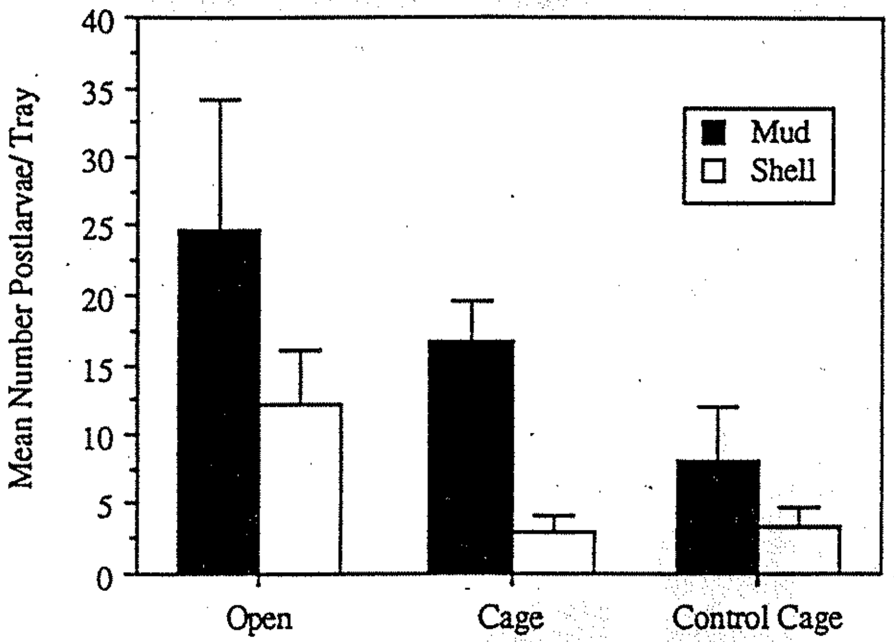


Figure 4.5 Results of a field experiment examining settlement of ghost shrimp postlarvae into 0.25-m^2 trays as a function of substrate (mud and shell) and cage structure (open, cage, and control cage). There was a significant substrate effect and a non-significant cage effect [cages and control cages (1.3-cm mesh) were used to test whether predators had an impact on postlarval settlement patterns over the duration of the experiment]. Values are mean densities of postlarvae/tray/72 h. Vertical bars are 1 SE (Feldman et al. in press).

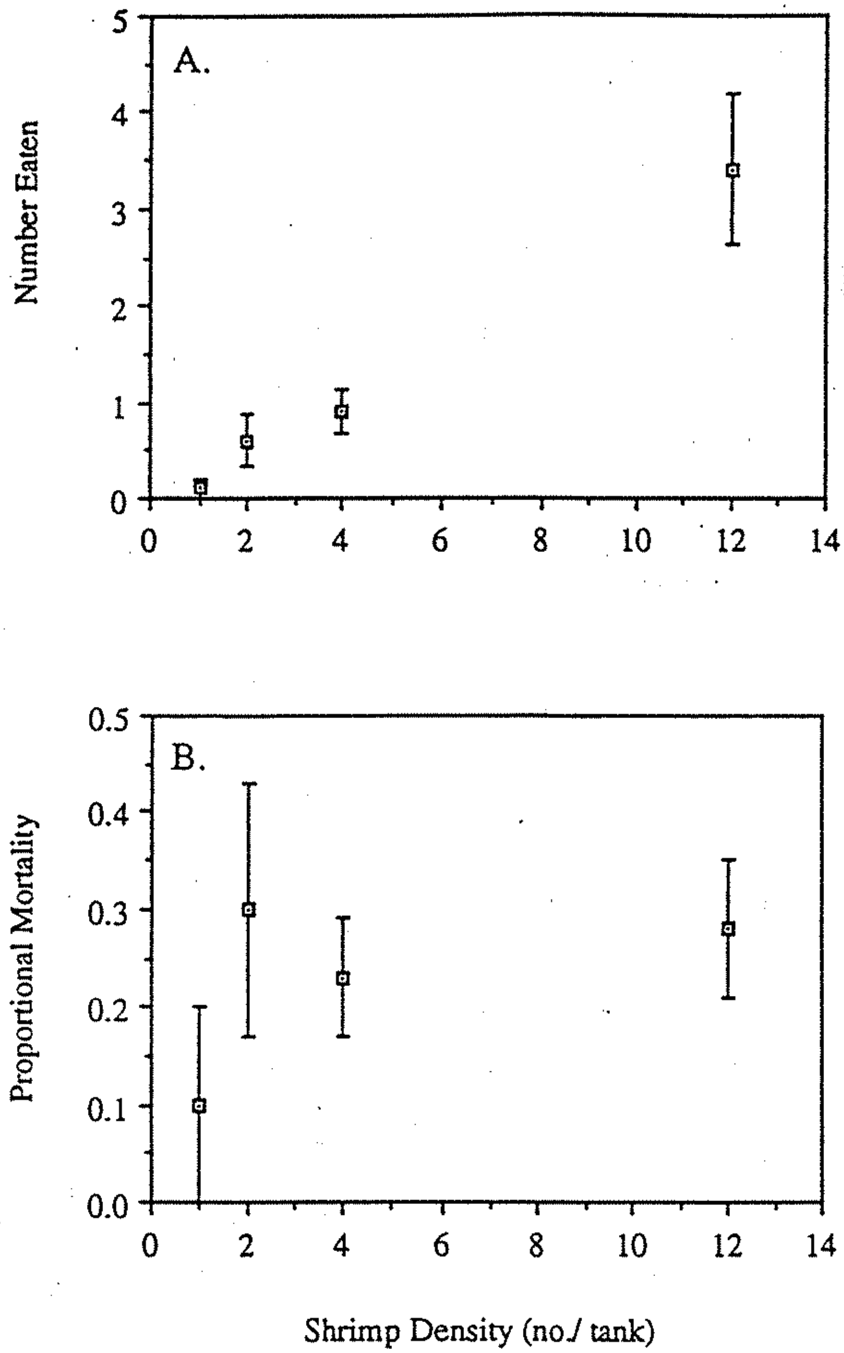


Figure 4.6 Results of a predation experiment examining YOY Dungeness crab (J5 and J6 Instars, 19.5 mm - 25.4 mm CW and 25.5 mm - 31.4 mm CW, respectively) predation on a range of YOY ghost shrimp densities. Mean values (±1 SE) are plotted for (A) consumption rate (no. shrimp eaten/crab/24 h) and (B) proportional mortality [(no. shrimp present)/crab/24 h] (Feldman et al. in press).

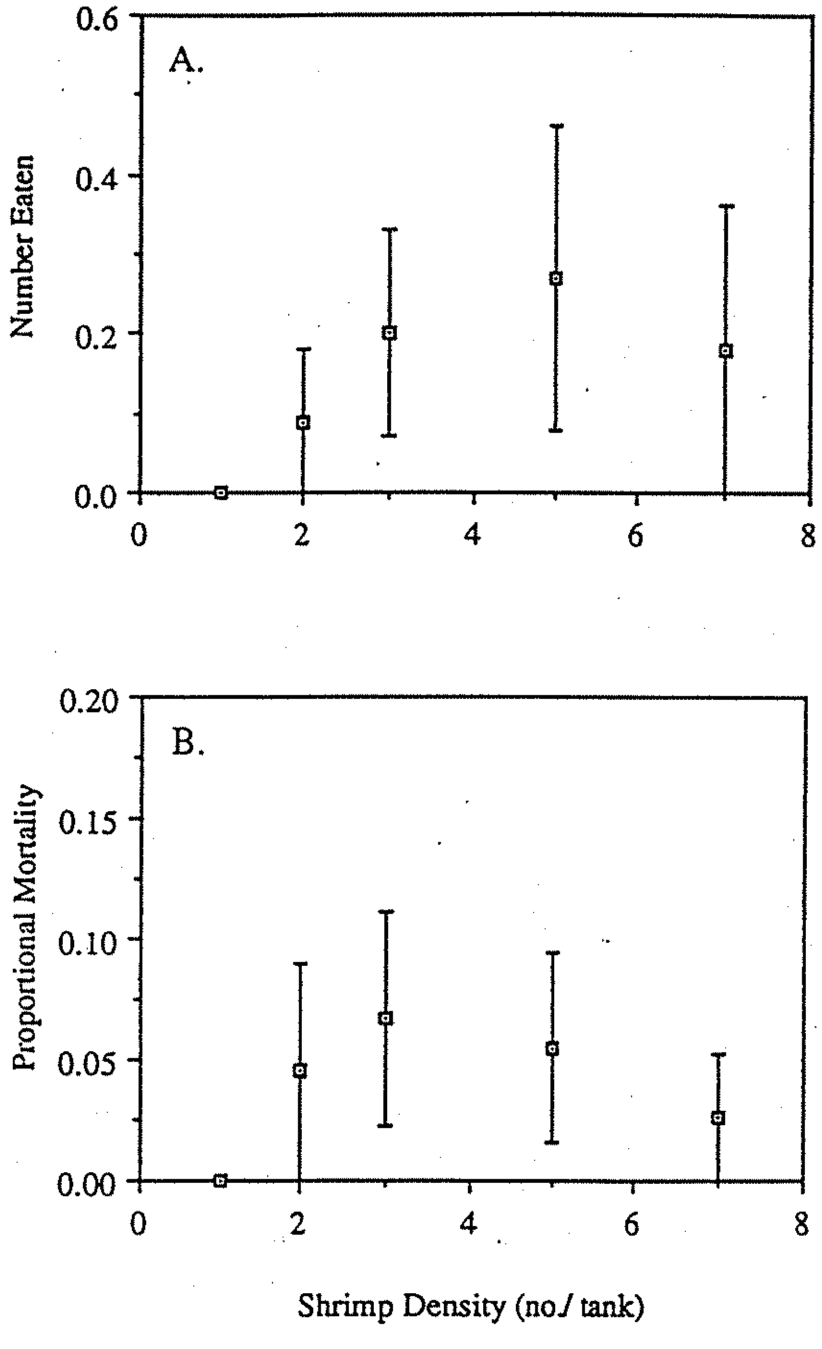


Figure 4.7 Results of a predation experiment examining YOY Dungeness crab (J3 Instar; 12.5 mm - 15.4 mm CW) predation on a range of YOY mud shrimp densities. Mean values (±1 SE) are plotted for (A) consumption rate (no. shrimp eaten/crab/24 h) and (B) proportional mortality [(no. shrimp present)/crab/24 h] (Feldman et al. in press).

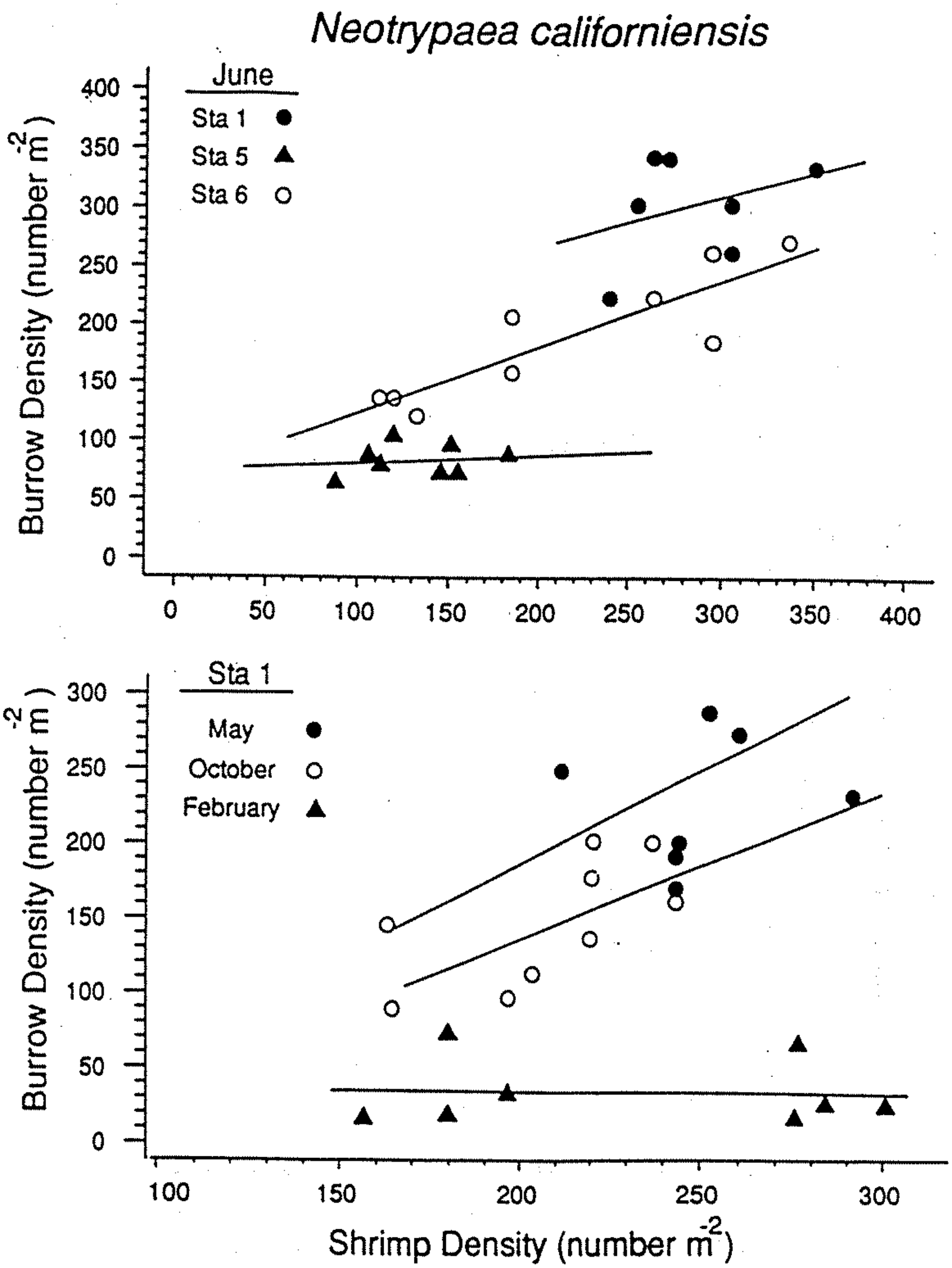


Figure 4.8 Relationship between burrow opening density and density of *Neotrypaea* (from core samples) at several locations (top) during June 1990 and at Sta. 1 during several different months 1989/90 (bottom). Both time of year and location significantly affected the relationship and there was no positive correspondence between openings and shrimp density at some stations and during winter months (Dumbauld 1994).

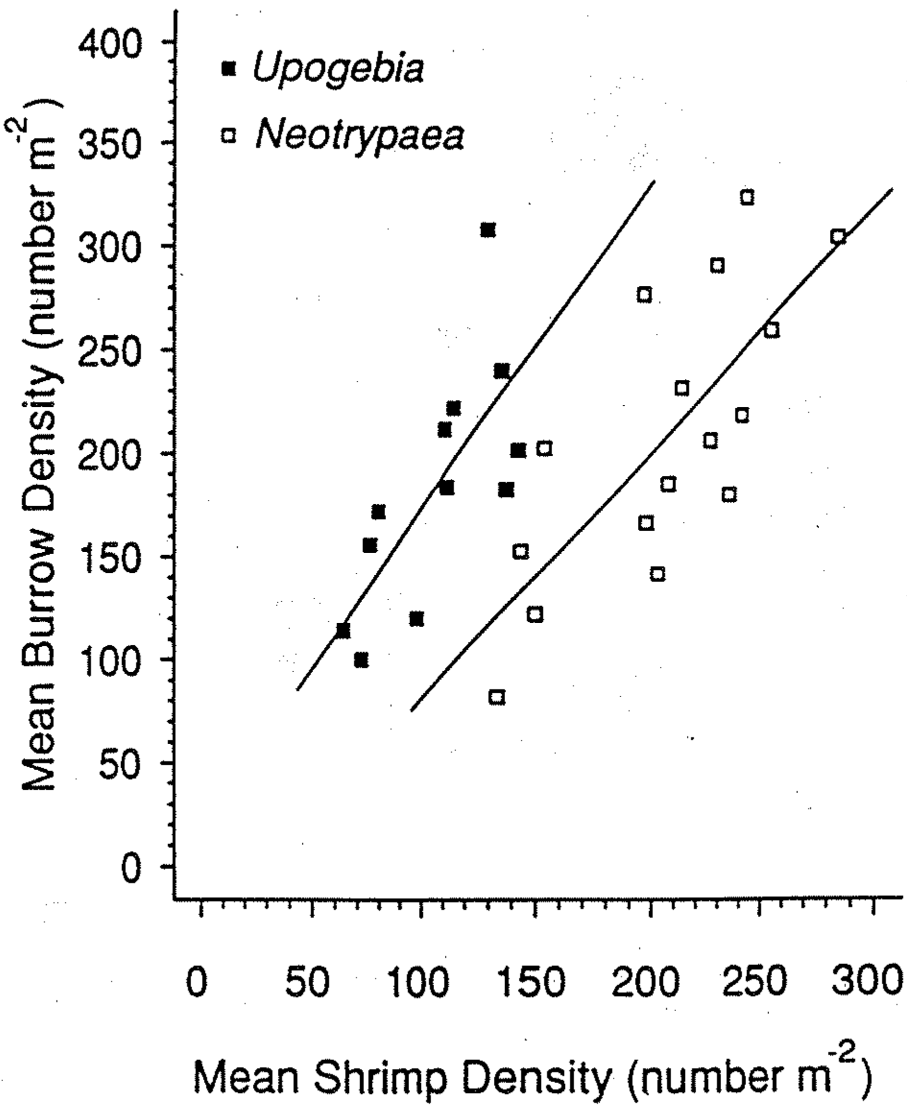


Figure 4.9 Relationship between average burrow opening density and average shrimp density for both species at stations 1 and 2 during summer months (May - Oct). The slope of the relationship was 1.5 burrows/shrimp for *Upogebia* and 1.2 burrows/shrimp for *Neotrypaea* (Dumbauld et al. 1996).

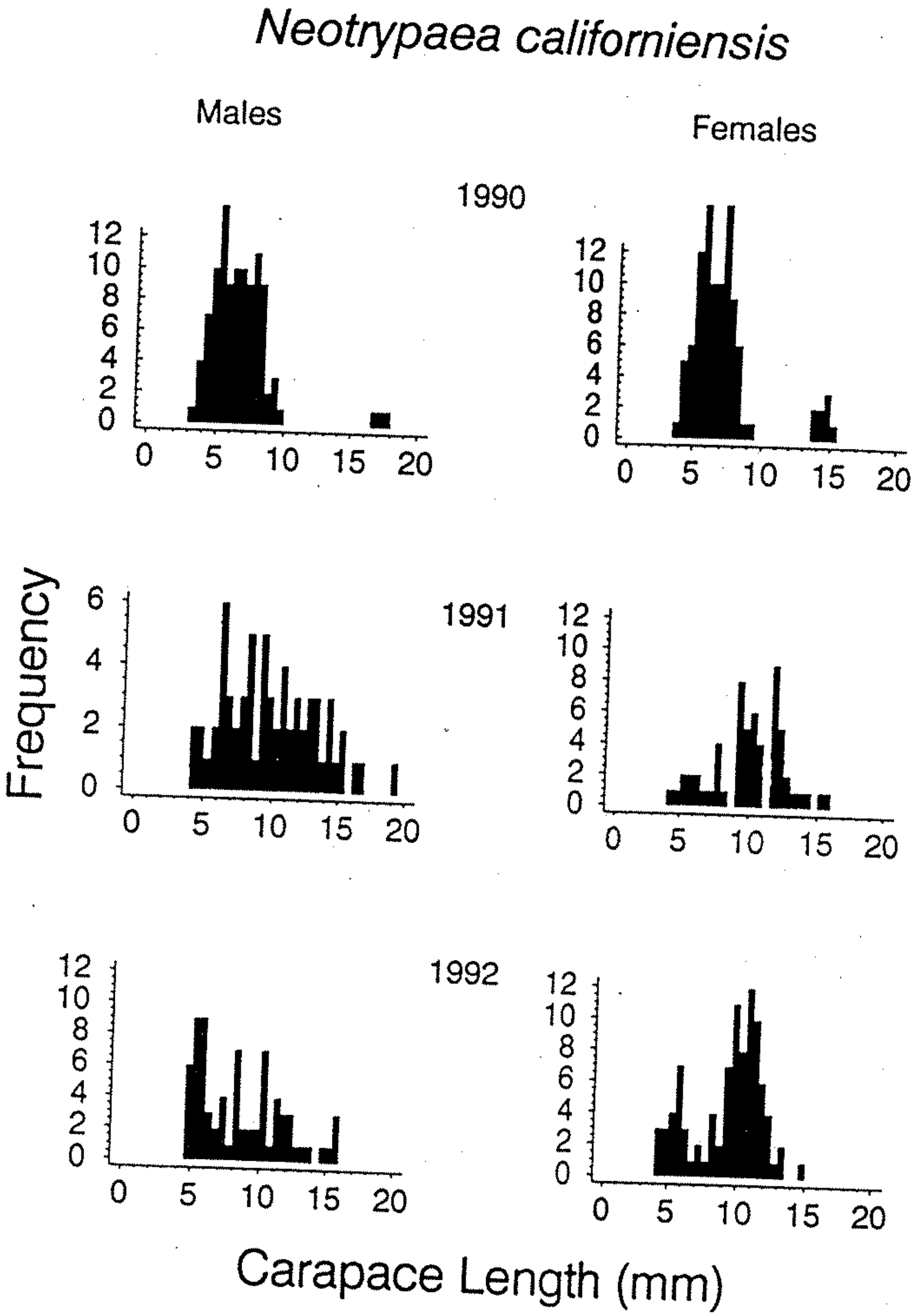


Figure 4.10 Length-frequency histograms of male and female ghost shrimp from 1990 through 1992 on experimental plots (n = 4) sprayed with carbaryl at 5.6 kg/ha in 1989 along the Palix River channel in Willapa Bay, Washington. Length-frequency histograms were analyzed using MIX to identify modes and corresponding age classes and to estimate mortality of the 1989 year class (see text and Tables 4.4, 4.5, and 4.6) (B. Dumbauld, unpubl. data).

Table 4.1. Recruitment densities of Young-of-the-Year (YOY) ghost shrimp measured at four locations in Willapa Bay, Washington, over a period of 5 years. Samples were taken in late September or October each year to 15-cm depth with a 25-cm diameter core. Shrimp densities are recorded as recruits/m^2 (B. Dumbauld, unpubl. data).

Location/ Year	Goose Point			Palix River			Nahcotta - Location 1			Nahcotta - Location 2		
	x	SD	n	x	SD	n	x	SD	n	x	SD	n
1992	**22**	38	9	ns	-	-	ns	-	-	ns	-	-
1993	ns	-	-	**144**	38	5	**60**	100	3	ns	-	-
1994	**48**	65	10	**22**	56	10	**13**	24	6	**30**	22	12
1995	**0**	-	10	**0**	-	10	**0**	-	10	**2**	6	12
1996	**2**	6	10	**0**	-	-	**6**	19	10	snp	-	-

ns = no samples taken
snp = samples not processed

Table 4.2 Net population growth rate of shrimp burrow openings (b/m^2/yr) on oyster beds based on WDFW burrow-count data.

	Ghost Shrimp b/m^2/yr	Mud Shrimp b/m^2/yr	Mixed Population b/m^2/yr
mean	3	5	7.2
sd	2.1	3.2	6.2
cv (%)	71.9	63.9	86
min	0.3	0.6	0.8
max	5.5	12.7	30
n	4	51	64

Table 4.3 Net rate of population growth for burrowing shrimp based on actual shrimp densities or burrow openings (b). Data set for Palix River site population (B. Dumbauld, unpublished data).

	Ghost Shrimp		Mud Shrimp	
	shrimp/m^2/yr	b/m^2/yr	shrimp/m^2/yr	b/m^2/yr
Mean	36.3	24.3	9.6	12.0
sd	60.1	109.7	27.7	75.5
cv%	165%	451%	288%	629%
Min	-46	-109	-20	-58
Max	124	206	51	136
n	6	6	5	5

Table 4.4 Summary of "natural mortality" estimates for male and female ghost shrimp based on data collected from a field experiment conducted by Dumbauld (1994). Between years, Z was calculated based on the exponential model dN/dt = -ZN. An overall estimate of Z from ages 1 to 3 was calculated based on simple linear regression of natural log-transformed abundances over the period 1990-1992.

Gender	Year	Numbers of shrimp	% annual "survival"	"Z"	Standard error	r^2
Male	1990	100				
	1991	31	31	1.17		
	1992	6	19	1.64		
	Overall "Z"			1.41	0.14	99
Female	1990	182				
	1991	39	21	1.54		
	1992	113	290	-1.06		
	Overall "Z"			0.24	0.75	9

Table 4.5 Results of MIX analyses on male ghost shrimp. Experimental plots sprayed with carbaryl at a concentration of 5.6 kg/ha in August 1989 were sampled again August 1990, 1991, and 1992. Age classes (i.e. 1+, 2+, 3+) were determined by fitting lognormal components to length-frequency histograms. Mean carapace lengths (CL), proportions, and numbers of males are given for each age class. Total numbers of male shrimp (calculated as the sum total of males in 4 core samples) were multiplied by the proportion of shrimp in each age class to calculate the number of males in each age class. A mortality estimate was derived based on changes in the numbers of males comprising the 1989 year class from 1990 to 1992 (see boxed numbers). Note the presence of three 1+ cohorts (modes) in 1990 and two 2+ cohorts in 1991 and 1992. Note also the presence of older (3+) males in 1991 that most likely immigrated into plots. If, instead, they were shrimp that had survived carbaryl treatment in 1989, they likely would have been present in samples as 2+ shrimp in 1990. (B. Dumbauld, unpubl. data).

Year	Variables	Total number of male shrimp	1+	1+	1+	2+	2+	3+
1990	Mean CL (mm)		4.1	5.4	7.5			
	Proportion males in age class		0.12	0.39	0.49			
	Number males in age class	100	12	39	49			
1991	Mean CL (mm)		4.5	6.4		8.7	11.2	14.1
	Proportion males in age class		0.07	0.21		0.25	0.24	0.23
	Number males in age class	63	4	13		16	15	15
1992	Mean CL (mm)		5.4			8.0	11.1	15.6
	Proportion males in age class		0.38			0.23	0.31	0.08
	Number males in age class	73	28			17	23	6

Table 4.6 Results of MIX analyses on female ghost shrimp. Experimental plots sprayed with carbaryl at a concentration of 5.6 kg/ha in August 1989 were sampled again August 1990, 1991, and 1992. Age classes (i.e. 1+, 2+, 3+) were determined by fitting lognormal components to length frequency histograms. Mean carapace lengths (CL), proportions, and numbers of females are given for each age class. Total numbers of female shrimp (calculated as the sum total of females in 4 core samples) were multiplied by the proportion of shrimp in each age class to calculate the number of shrimp in each age class. A mortality estimate was then derived based on changes in the numbers of females comprising the 1989 year class from 1990 to 1992 (see boxed numbers). Note the presence of two 1+ cohorts (modes) in 1990 and 1992, and the presence of older (3+) females in 1991 that most likely immigrated into plots (B. Dumbauld, unpubl. data).

Year	Variables	Total number of female shrimp	1+	1+	2+	2+	3+
1990	Mean CL (mm)		5.1	6.8			
	Proportion females in age class		0.30	0.70			
	Number females in age class	182	55	127			
1991	Mean CL (mm)		5.5		9.3		11.8
	Proportion females in age class		0.16		0.34		0.50
	Number females in age class	116	19		39		58
1992	Mean CL (mm)		4.6	6.0	8.6		10.8
	Proportion females in age class		0.09	0.16	0.13		0.62
	Number females in age class	73	16	29	24		113

5.0 OYSTER GROWING METHODS

Pacific oysters (*Crassostrea gigas*) can be grown using a variety of distinct methods, each of which has many minor variations. Culture methods can be classified by the proximity of the oysters to the sediment surface: bottom culture (in which oysters are grown on the ocean bottom or sediment surface) and suspended culture in which oysters are grown above the sediment surface (this includes longline, tray, string, stake, and stick culture) (Magoon and Vining 1981; Quayle 1988; Nosho 1989). Each method has requirements linked to the physical and nutritive conditions at the site where farming is to be done, and selection of the appropriate method is usually based on growing conditions, legal considerations, and the market for oysters (i.e., as halfshell [single oysters] or as shellstock [shucked meat]) (Brown and Roland 1987).

The principal growing methods are summarized below, followed by an evaluation their potential for use in Willapa Bay and Grays Harbor estuaries. For more authoritative and thorough descriptions of oyster growing methods for *C. gigas*, consult Magoon and Vining (1981), Else (1987), Quayle (1988), Nosho (1989), and references cited therein.

5.1 BOTTOM CULTURE

As the name implies, oysters are grown on the surface of the intertidal or subtidal flats. Worldwide, bottom culture is the most widely used and least expensive method of growing oysters (Quayle 1988). Bottom culture is practiced extensively in North America, Europe, Oceania, Australia, and Asia (Angell 1986). This method mimics the natural growth habit of most oysters, which typically form reefs on the seabed. Bottom culture differs from natural oyster reefs in that oysters are grown as a "monolayer" rather than a mound, and typically only one age-class of oyster is present in bottom culture, as opposed to mixed-age natural populations. Bottom culture is usually conducted on natural substrates of sand to sandy-mud. The coarser the substrate, the greater the prospect that strong currents will be present that could move or damage oysters; gravel or cobble beaches are indicative of strong currents. Other factors affecting site suitability include tidal height, salinity, water quality, predators, land ownership, burrowing shrimp density, turbidity, eelgrass, phytoplankton productivity, temperature, and accessibility (not necessarily listed in order of importance).

Oyster farmers that we surveyed reported that in Willapa Bay and Grays Harbor, the general practice of intertidal bottom culture is to spread the "cultch" or "seed" (i.e., oyster spat settled onto a non-living oyster shell) onto seed beds in the spring or summer of year 1, break the clusters of oysters into small clumps to reduce competition and enhance growth rate in fall of year 1 or spring of year 2, transfer the oysters to "growing" or "fattening" beds in spring or summer of year 2, and harvest in summer of year 3 through winter of year 4. This schedule is affected by rates of growth of oysters on particular beds, market conditions, susceptibility of the crop to damage by predators or burrowing shrimp, and weather. Prior to spreading, bags of seed are sometimes set out on the seed beds for a few weeks prior to spreading to await the best conditions or availability of laborers to do the work. Additionally, oysters may be transplanted to growing beds before being moved to fattening beds. Bottom culture in Willapa Bay and Grays Harbor can utilize grounds with elevations between +3 ft and -3 ft MLLW (Carkner and Harbell 1992). In some cases, oysters are grown from seed to market size on the same ground, but typically seed beds are located higher in the intertidal (where turbidity, silting, and predation are reduced, yet growth rates are lower) and fattening beds are located in the lower intertidal where growth rates are maximized and the larger, older oysters are more resilient to silting, turbidity, and predators (Quayle 1988). However, many factors influence how a piece of property is farmed, including sediment type, exposure to currents and storm surge, and the history of burrowing shrimp impacts. Most bottom culture in Willapa Bay and Grays Harbor is conducted in the intertidal zone rather than subtidally because of most of the land in the estuary is intertidal and that which is subtidal is principally used as navigation channels (in which case, oyster farming would interfere with other boat traffic). Bottom cultured oysters in Washington State are primarily grown for the shucked meat or shellstock market.

Most aspects of bottom culture maintenance can be mechanized, although some farmers use manual labor in part. Seed can be spread from boats at high tide (or distributed by hand at low tide), cluster separation can be done at high tide by boat-towed spring-toothed harrows (or broken by hand using rakes, hammers, or rods at low tide), and retrieval of oysters for transplanting or harvest can be done by drag dredging (or by hand picking). Mechanization can greatly reduce costs and allow greater acreage to be farmed by fewer workers, but capital expenses and equipment maintenance costs can add be prohibitive for small acreage farmers.

Burrowing shrimp have a strong and direct detrimental affect on bottom-cultured oysters primarily because the oysters are grown on the substrate inhabited by the shrimp. Living on the sediment surface, these oysters are susceptible to burial by sediment resuspended by the bioturbation of the shrimp. Seed oysters seem to be especially susceptible to burial by burrowing shrimp, possibly because relatively less sediment is required to smother a small, thin oyster than a large, thick oyster. Additionally, it is suspected that oysters may sink into the sediment caused by the fluidization of the substrate by the burrowing shrimp, resuspended sediments may interfere with the oysters' filter-feeding behavior, or oysters may compete with burrowing shrimp for food. However, evidence for these latter mechanisms of burrowing shrimp impact is only anecdotal.

5.2 STAKE CULTURE

In this method, cultch is attached to the top or sides of stakes that are driven into the sediment (Fig. 5.1). Stakes are usually set in the intertidal zone, though they can be set subtidally. Stakes are usually set about 2 ft apart and arrayed in rows parallel to the water line, with rows spaced approximately 8 ft apart to allow adequate growth and accessibility for maintenance and harvest (Nosho 1989). The length of the stakes and attachment of oysters must be such that each oyster is submerged at high tide. Stake culture is practiced extensively in China, the Philippines, many tropical nations, and to a small extent in North America, including Grays Harbor and Puget Sound (Angell 1986; Quayle 1988; Nosho 1989). In Washington State, stake-cultured oysters are produced primarily for the single or halfshell market.

A variant of stake culture is stick culture in which boards encrusted with spat are attached horizontally to the top of stakes (Quayle 1988). Each stick may be supported by more than one stake, depending on the length and strength of the sticks and stakes. The stick culture method has been used for centuries and is used in Australia and New Zealand (Quayle 1988).

Stake culture is often used on substrates too soft for bottom culture. Stake cultures must be protected from currents and storms, because the stakes are susceptible to scouring and being toppled by strong wind and waves. Typically, production is lower than that for bottom culture or other forms of suspended culture, and the oysters are grown for the halfshell market (Quayle 1988; Nosho 1989). The culture cycle typically requires two summers of growth for oysters to reach market size (Quayle 1988). Some portion of the harvest is obtained as bottom culture from oysters that fall off the stakes. All aspects of the culturing are conducted by hand, and there seems to be little opportunity for mechanization (Quayle 1988).

Stake culture is susceptible to burrowing shrimp in several ways. The stakes may become de-stabilized by the softening of the sediment caused by the deeply burrowing shrimp; this can cause the stakes to topple and drive some oysters into the sediment. Secondly, oysters that fall off the stakes are susceptible to burial in the same manner as bottom-cultured oysters. Oysters on standing stakes are relatively free from direct interaction with burrowing shrimp, but may be susceptible to feeding interference (clogged gills) and food competition to the same extent as other near-bottom oysters.

5.3 FLOATING CULTURE

In floating culture, oysters are grown on lines that are suspended from a raft or float (Fig. 5.2). There are many variants to this method, with different types of floats, different methods for anchoring the floats, different ways to attach and suspend the oysters from the floats, and different depths at which the oysters are deployed (Quayle 1988). Typically, cultch is strung on lines at intervals of 8 in. to 12 in., and the length of the line is set to keep the oysters within the most productive, algal-rich layers of water. Floating culture does not require access to tidelands and can be practiced in deep water. For these two reasons, floating culture is popular along shores unsuitable for bottom culture in Canada, Japan, China, Malaysia, Sierra Leone, Venezuela, Puerto Rico, and Puget Sound (Angell 1986; Quayle 1988; Nosho 1989).

Two variants on the floating culture method that are practiced in the Pacific Northwest are tray culture and net culture. The tray method has oysters placed on perforated racks that are suspended from floats or rafts. The net method uses Japanese lantern nets suspended from floats in which oysters are placed on successive tiers and enclosed within a mesh. Both methods are used in Alaska and British Columbia, Canada (Else 1987; Quayle 1988), and the net method is used in parts of the San Juan Islands, Washington (Nosho 1989). These methods are also used elsewhere in the world (Angell 1986). In Washington State, most oysters raised by floating culture are sold to the single oyster or halfshell market.

Sufficient floatation must be provided to suspend the full weight of mature oysters; otherwise, the lines and oysters will sink. Floats can include rafts, floating docks, and buoys. Floating culture must be sited in water deep enough to keep the lines off the seabed at low tide because the oysters can be smothered in the sediment and the lines can snag on the bottom, which could damage or destroy the line or float. However, floating cultures must not be sited within navigable waterways as they might interfere with boat traffic. Finally, floating cultures must be reasonably well protected from wave action so that the floats and lines will not be subjected to lateral stresses that can tear the culture system apart.

Production per unit area can be ten times greater than that of bottom culture, the production cycle can be as short as 1.5 yr under ideal conditions, and the condition and flavor of the oysters can be better than those produced by bottom culture (Quayle 1988). However, the capital and maintenance costs for floating culture are considerably higher than those for simple bottom culture. Rafts, floats, and anchors can be expensive to purchase (or construct) and maintain. The floats and lines of oysters are susceptible to fouling by barnacles, hydroids, tunicates, other invertebrates, and algae which can amount to 50% of the total weight of a line, which obviously adds to the drag on the flotation system. Furthermore, fouling can reduce the water flow and food supply to the oysters. Removal of fouling organisms, thinning the oysters to promote more rapid growth, and harvesting are not mechanized (with the exception of winches to haul the lines) and, thus, labor intensive.

Floating culture is relatively unaffected by burrowing shrimp. The only negative impacts burrowing shrimp might exert would be in causing the anchors to sink deeper into the sediment or in competition with the oysters for food. The former is unlikely because burrowing shrimp do not usually extend into deep water (>10 ft), and little evidence exists to support the latter.

5.4 RACK CULTURE

This method is a hybrid of floating culture and stake culture in that lines of oysters are suspended from racks or posts that are anchored to the substrate (Fig. 5.3). Racks consist of single or parallel horizontal beams are supported by posts or tripods about 3 ft to 4 ft above the substrate (Quayle 1988). Rack culture is typically conducted in the intertidal or shallow subtidal so that workers can walk or wade to the oysters. As with floating culture, lines may be rope or wire, and should not be so long that they touch the sediment surface. As with stake culture, the racks can be constructed in soft sediments and must be located in sufficiently quiet waters that the posts and beams are not damaged by currents and waves. The production cycle and growth rates of oysters should be very comparable to stake culture. Traditional rack culture is used in Australia, the Philippines, Indonesia, and Cuba.

5.4.1 Longline Culture. Longline culture is a variant of rack culture used extensively in Grays Harbor and the second most widely used method in Willapa Bay (Nosho 1989). Cultch is inserted into stranded nylon rope, which is then strung from PVC posts approximately 2 ft from the sediment surface (Fig. 5.4). Posts are typically arrayed at 5-ft intervals and pushed approximately 2 ft into the sediment (Tice and Griffin 1993). Longlines are strung parallel to the water's edge, and rows of line are spaced ~8 ft apart to allow adequate water flow and accessibility for maintenance and harvest. Growers that we interviewed reported a culture cycle of setting out bags of seed oysters in the fall, stringing ropes in the late winter and spring, and harvesting a year or two later. After harvest, the posts are often removed, the ground harrowed, and new posts set out; however, some growers may elect to leave posts in place over more than one culturing cycle. As with rack culture and stake culture, all aspects of longline culture are conducted manually. Oysters are harvested continuously over a period of several months (up to two years), whereby the appropriate-sized oysters can be collected as needed to meet the market demand (Brady Engvall, Brady's Oysters). Because lines must be maintained manually and the oysters cannot be moved before harvest, longline culture is only possible on intertidal ground with an elevation of 0 to +2 ft above MLLW (Carkner and Harbell 1992). A third to a half of the harvest is from oysters that fall off the lines and are bottom cultured under the suspended oysters. Longline cultured oysters in Washington State are produced for the halfshell and, to a lesser extent, the shellstock market.

5.4.2 Rack and Bag Culture. Another variant of rack culture used in Willapa Bay and Grays Harbor is rack and bag culture (Fig. 5.5). Essentially, cultch is enclosed as a monolayer within a plastic mesh bag (2 ft x 3 ft) or polyethylene cage, and the bag (or cage) is attached to a rebar rack that is mounted on the tide flat (Nosho 1989). Usually several bags are attached to a single rack. As the seed grows, the oysters are transferred to bags with coarser mesh, and the clusters are broken up to reduce competition between oysters. The bags or cages are flipped over approximately every 2 weeks to reposition the oysters, reduce fouling, and knock silt off the oysters. Thus, rack and bag culture requires considerable maintenance, but some effort is reduced because the oysters are loose within the bags or cages, and each container can be handled by an individual. Because bags and cages must be maintained manually, rack and bag culture is only possible on intertidal ground with an elevation of 0 to +2 ft above MLLW (Carkner and Harbell 1992). Rack and bag cultured oysters in Washington State are primarily produced for the single oyster or halfshell market.

Rack cultures are susceptible to many of the problems of both stake and floating culture. The posts are vulnerable to scour from currents and waves and toppling or sinking into the substrate. The lines, bags, or cages are vulnerable to fouling, which can exert additional weight and drag on the supporting structures and reduce the flow of water and food to the oysters. Few aspects of rack culturing have been mechanized.

Burrowing shrimp can have a considerable impact on rack cultures. First, their burrowing can soften the sediment around the posts, which can lead to their sinking or toppling. Second, oysters that fall off the lines can be buried in the same manner as intentionally bottom-cultured oysters. As with all other forms of oyster culture, there is also the potential for food competition between rack-cultured oysters and burrowing shrimp, but no data are available to adequately test this hypothesis.

5.5 EVALUATION OF OYSTER CULTURE METHODS FOR WILLAPA BAY AND GRAYS HARBOR

The oyster industry in Washington state began in the 1850s with the harvest of native Olympia oysters (*Ostrea lurida*) in Willapa Bay and Puget Sound. The Pacific oyster was introduced from Japan in the 1920s in response to dwindling stocks of native oysters and the failure of Eastern oysters to succeed as a replacement. Commercial oyster production in Willapa Bay peaked in the mid-1940s at greater than 1.5 million gal of meat. Oyster seed was imported from Japan until it was replaced by local hatchery produced seed in the late 1970s. A "natural" set also produces local seed in Willapa Bay one out of every three years (B. Dumbauld, pers. comm.) The Willapa Bay-Grays Harbor region is presently the largest oyster producing area on the U.S. west coast, with an annual production of approximately 700,000 gal of meat and the direct and indirect employment of over 1700 people in the region (Conway 1991; Carkner and Harbell 1992).

Presently, approximately 33% of the total area of Willapa Bay (~26,000 acres) is classified as oyster lands, of which only about 6,200 acres are fattening and growing ground that produce market-quality oysters (WDF/WDOE 1992) (Fig. 5.6). In Willapa Bay, most oysters are grown using bottom culture methods, followed by longline culture and, to a much smaller extent, rack and bag culture (Dennis Tufts, Bendickson Oysters). In contrast, only about 900 acres of Grays Harbor (~1.6% of total area) are farmed for oysters (Fig. 5.7). In Grays Harbor, most oysters are grown using longline culture, followed by bottom culture, and some stake culture (Brady Engvall, Brady's Oysters). Further details of the history and economics of oyster farming in these two estuaries can be found in Shotwell (1977), WDF/WDOE (1985), WDF/WDOE (1992), Conway (1991), and Carkner and Harbell (1992).

Many of the oyster growers that we interviewed reported having experimented with different oyster culture methods. For example, raft culture has been tried in Grays Harbor (B. Engvall, pers. comm.) and stake and rack and bag culture have been tried in Willapa Bay (Randy Shuman, Metro, and Larry Skidmore, Shoalwater Oysters, pers. comm., and L. Bennett, pers. obs.). For a variety of reasons, most growers have settled on bottom culture and longline culture as the most practical methods for these estuaries.

5.5.1 Physical Considerations. Willapa Bay and Grays Harbor estuaries are very shallow and characterized by extensive tidal flats. Over 50% of the MHHW area of both bays is intertidal. Water deeper than 6 ft at low tide (MLLW) is almost entirely limited to navigation channels. This leaves very little area available for floating culture, which requires water sufficiently deep that oysters and lines suspended from floats will not touch the sediment. The available space for floating culture is further restricted by the need to allow the floats (or rafts) to swing about its anchor in all directions (i.e., move horizontally in response to current shifts to the extent of the scope of its anchor line), which can change substantially with the rise and fall of the tide. This will restrict the number of floating culture structures that could be packed into a parcel of water. Thus, floating culture would seem to be viable only to a very limited extent within these two estuaries.

As described previously, these estuaries are regularly (several times per year) hit by very strong storms that pack gale force winds that create waves and change current patterns within the bays. Physical structures anchored in the sediment must be able to withstand wind, storm currents and waves, and associated sediment movement and scouring. Thus, in the high energy, open, unprotected reaches of the estuaries, physical structures used for oyster culture or control of burrowing shrimp must be well anchored. These physical forces can also affect bottom-cultured oysters, and bed load transport of sediments and oysters on oyster beds during storms does occur (L. Bennett, pers. obs.). Floating culture would probably be most vulnerable to storm damage because the weight of the oysters and drag caused by winds, current, or waves would pull in opposite directions against the float, which could lead to failure of the line, anchor, or integrity of the float. Stake, rack, and bottom culture would therefore appear to be the best options in storm-prone intertidal areas.

Finally, the wide expanses of the tide flats and the softened substrate created by burrowing shrimp can restrict access to oyster cultures at low tide. This is especially problematic for labor-intensive oyster culture, such as stake, rack, longline, and rack and bag methods. These methods are not well suited to mechanization, and all aspects of the culture (setting seed, maintenance, and harvest) must be conducted on foot at low tide. Sediments with moderate to high densities of burrowing shrimp (>20 b/m^2) do not support much weight, and workers can quickly sink to their knees in such sediments (all authors, pers. obs.). Thus, longline and rack and bag culture operations are typically conducted along the margins of tide flats, adjacent to navigable tidal creeks, or on well-consolidated sand flats, so that workers can efficiently get to the oysters. Access to bottom-cultured oysters is similarly constrained for growers who do not use boats for harrowing and dredging, but most bottom culture growers do use machinery for these tasks because they allow greater areas to be farmed, greater efficiency than manual labor, and unlimited access to crops at low tide.

5.5.2 Susceptibility to Burrowing Shrimp. As was noted above, all forms of oyster culture are vulnerable to direct damage from burrowing shrimp, with the possible exception of floating culture. Bottom-cultured oysters can be buried by sediments excavated by the shrimp; stakes, posts, and racks can sink into or be toppled by sediments softened by the shrimp's burrowing; and oysters grown close to the substrate might have gills clogged by sediments resuspended by shrimp bioturbation. Indirect impacts in the form of competition for food might affect oysters regardless of cultural method, but there are no data to test this hypothesis. Thus, suspended culture methods (not including floating culture) will typically require some form of burrowing shrimp population control, as does bottom culture.

5.5.3 Economic Considerations. Carkner and Harbell (1992) compared the costs and return of bottom culture, longline culture, and rack and bag culture in Willapa Bay and Grays Harbor. Floating culture was not included because they, too, concluded that it is not viable in these estuaries because of the lack of deep water. Their evaluation was based on cost and production data provided by oyster growers from the region and used reasonable assumptions of equal crop rotation periods (3 yr), equal-sized farms, and equal market value for the harvest, but different yields and labor requirements for each culture method and different market demands and selling prices for half-shell and shellstock oysters. The following are conclusions from this study:

1) Economically, rack and bag culture is marginally viable for the half-shell market because production costs ($0.16 per oyster) are nearly equal to the selling price ($0.18 per oyster); it is not viable for growing shellstock because of high labor and materials costs ($0.27 per oyster).

2) Longline culture requires the same type of ground as do fattening beds in bottom culture, but cannot practically use the less productive grounds that bottom culture uses for seed beds. As the highly productive beds account for only ~25% of the oyster grounds, longline and rack and bag cultures would leave 75% of currently productive beds idle if these methods were used exclusively.

3) On average, longline culture has a higher overall productivity than does bottom culture, but has lower production on fattening ground. If bottom-cultured oysters are rotated through fattening beds every year, then the productivity of that ground could be double or triple the same bed than if longline culture had been used.

4) Longline culture is substantially more labor intensive than bottom culture, requiring 10 workers to harvest 750 bushels in a tide versus 2 workers for bottom culture. Large-scale longline culture operations have showed a net loss caused by high labor costs.

5) Shucking bottom-cultured oysters is less difficult than shucking longline-cultured oysters. The latter can become entangled with rope that can get entangled in processing plant machinery.

Thus, based on Carkner and Harbell's economic analysis, rack and bag culture and longline culture generate less income, per acre, than bottom culture for production of shellstock oysters. Both off-bottom culture methods are negatively affected by burrowing shrimp, as is bottom culture. Longline culture and rack and bag culture are well suited for production of halfshell oysters, and both seem to be sensible choices for steeper-profile tide flats that might be too narrow to efficiently farm by bottom culture. Longline culture would appear to be more profitable than rack and bag culture, based on the assumptions used in Carkner and Harbell's (1992) analysis. Traditional stake culture was not included in their analysis; however, we would expect its costs to be comparable to those of longline culture, minus the difference in labor costs to attach and maintain oysters to stakes vs. lines and costs of the line. Although we have no data, it would seem the yield from stake and longline culture would be comparable if the initial density of seed-per-acre were the same.

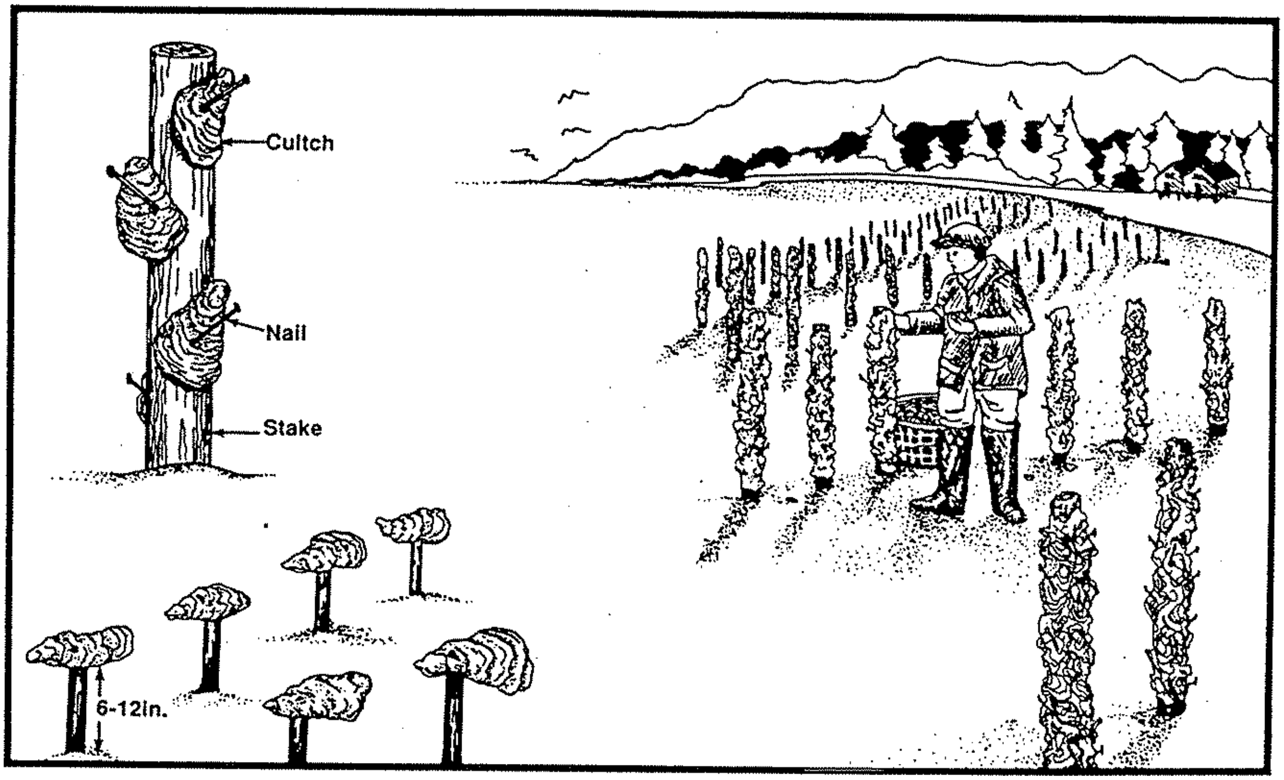


Figure 5.1. Stake culture of Pacific oysters (Nosho 1989).

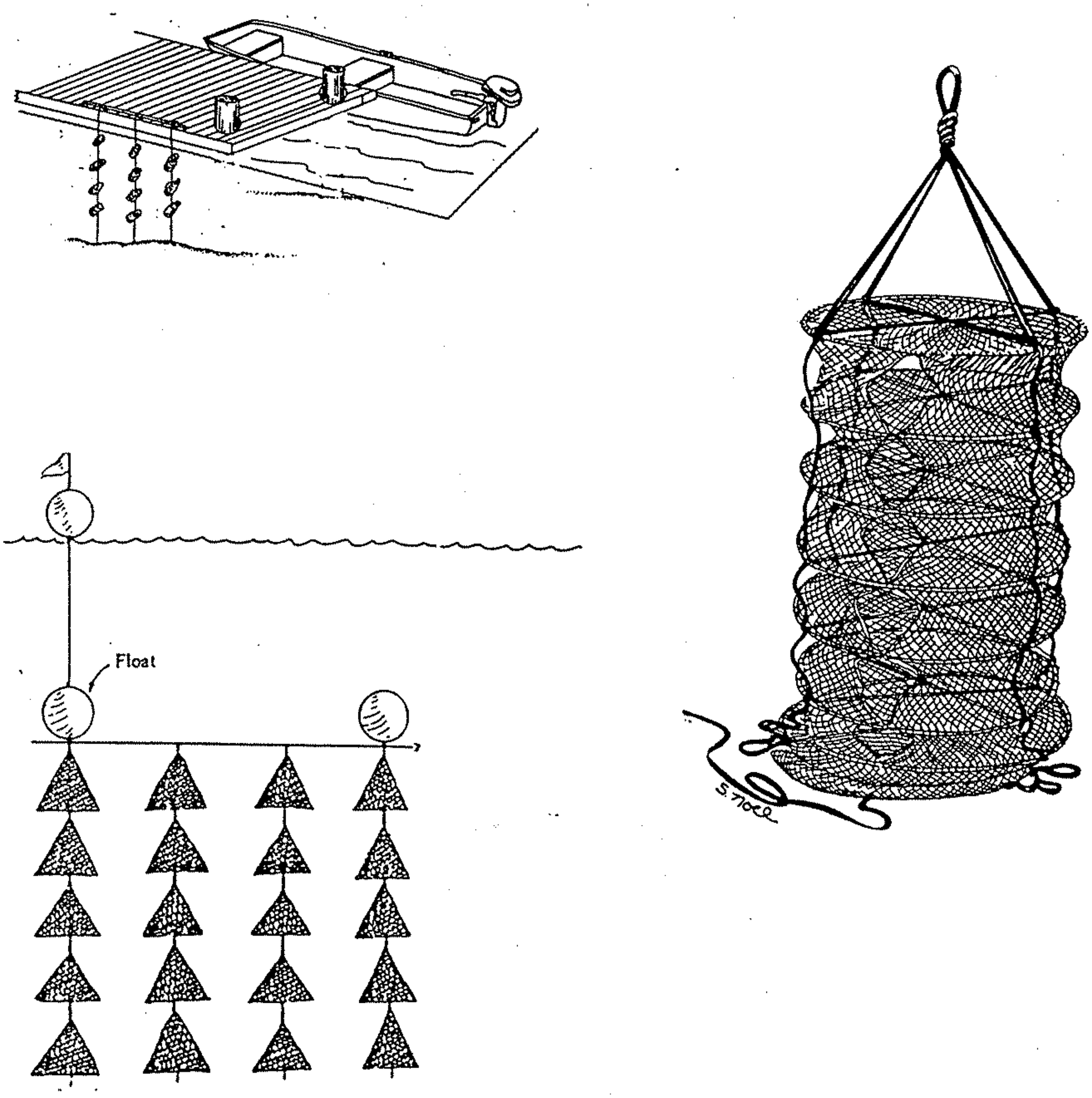


Figure 5.2. Floating culture of Pacific oysters (adapted from Nosho 1989, Quayle 1988, and 1987).

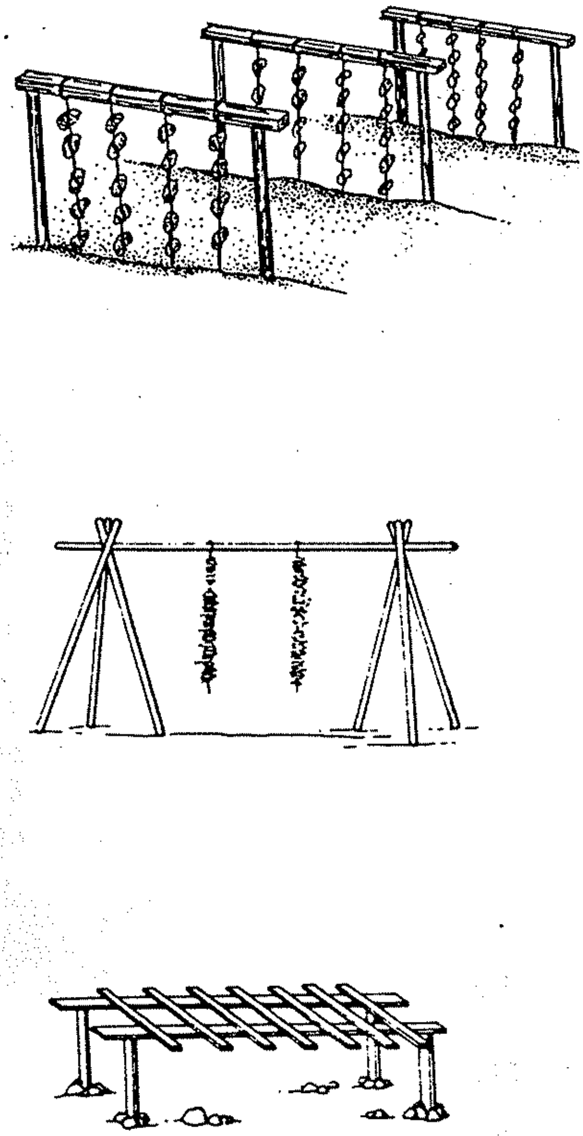


Figure 5.3. Rack culture of Pacific oysters (adapted from Quayle 1988 and Nosho 1989).

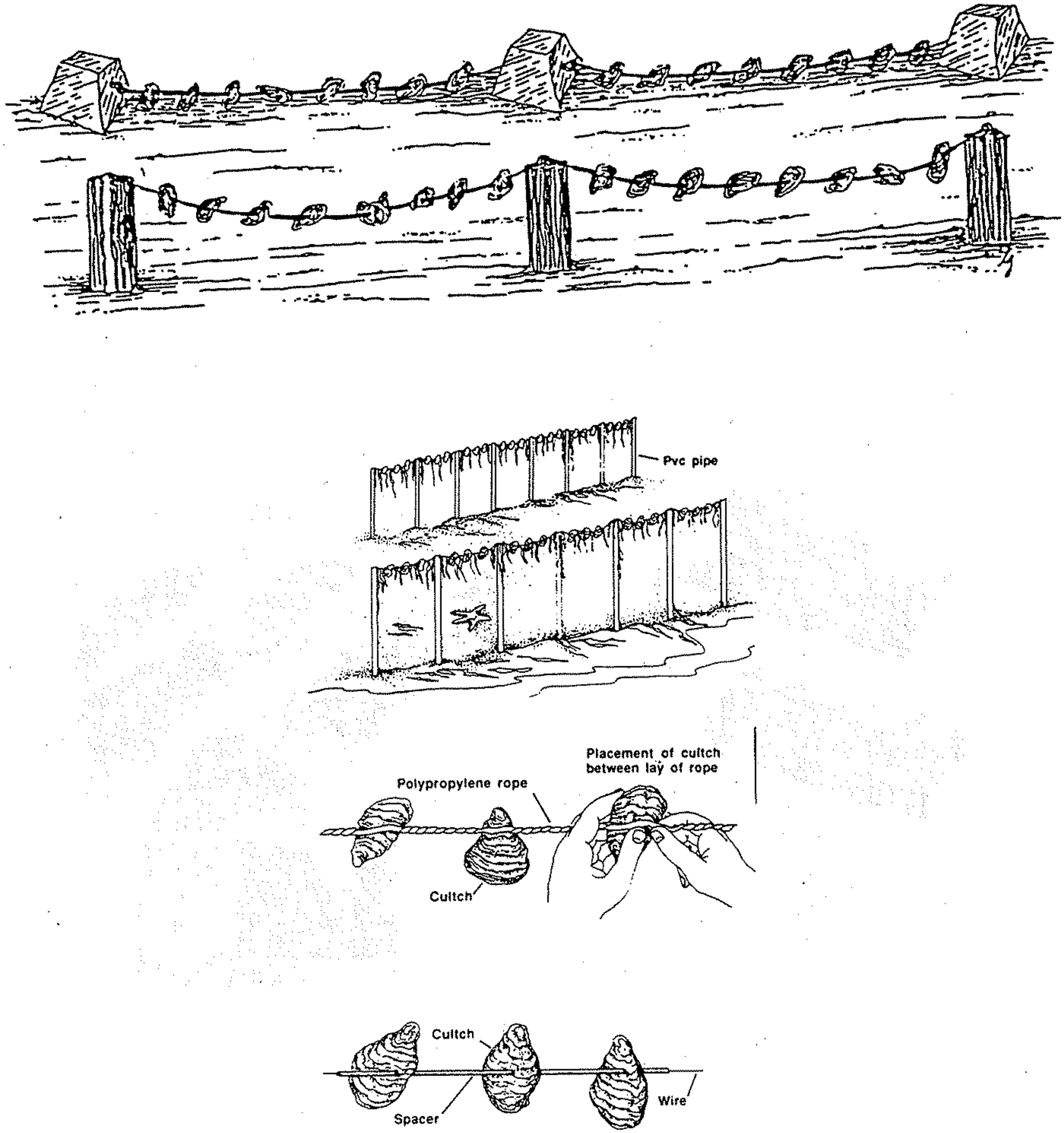


Figure 5.4 Longline culture of Pacific oysters (adapted from Else 1987 and Nosho 1989).

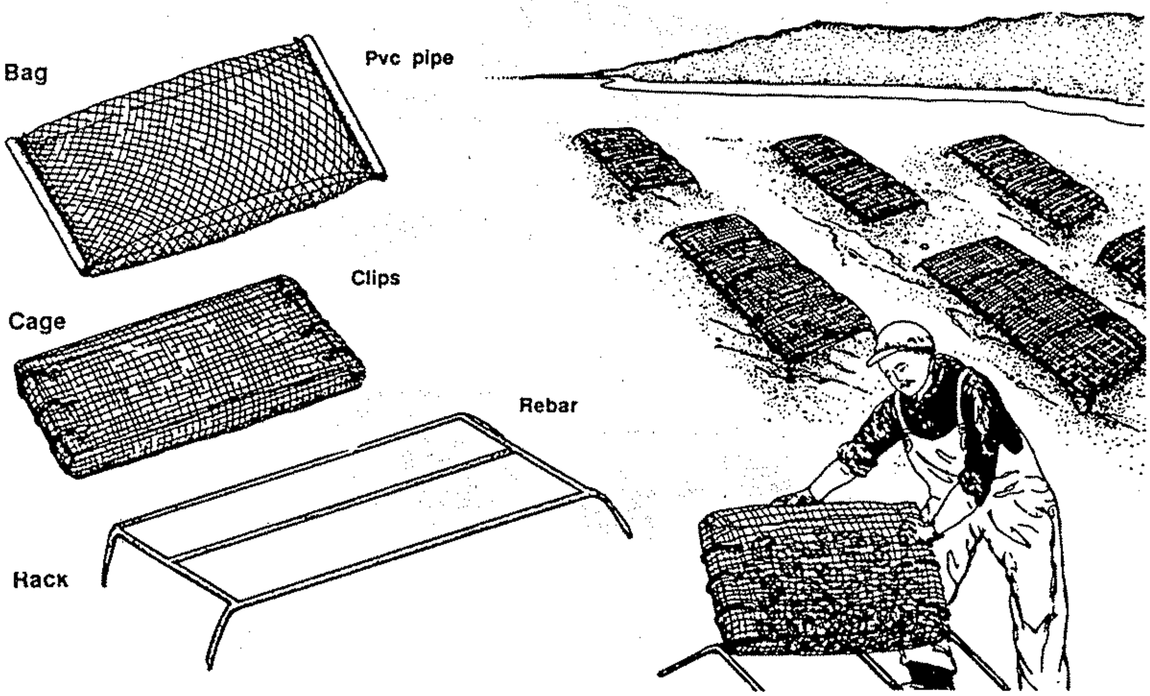


Figure 5.5 Rack and bag culture of Pacific oysters (Nosho 1989).

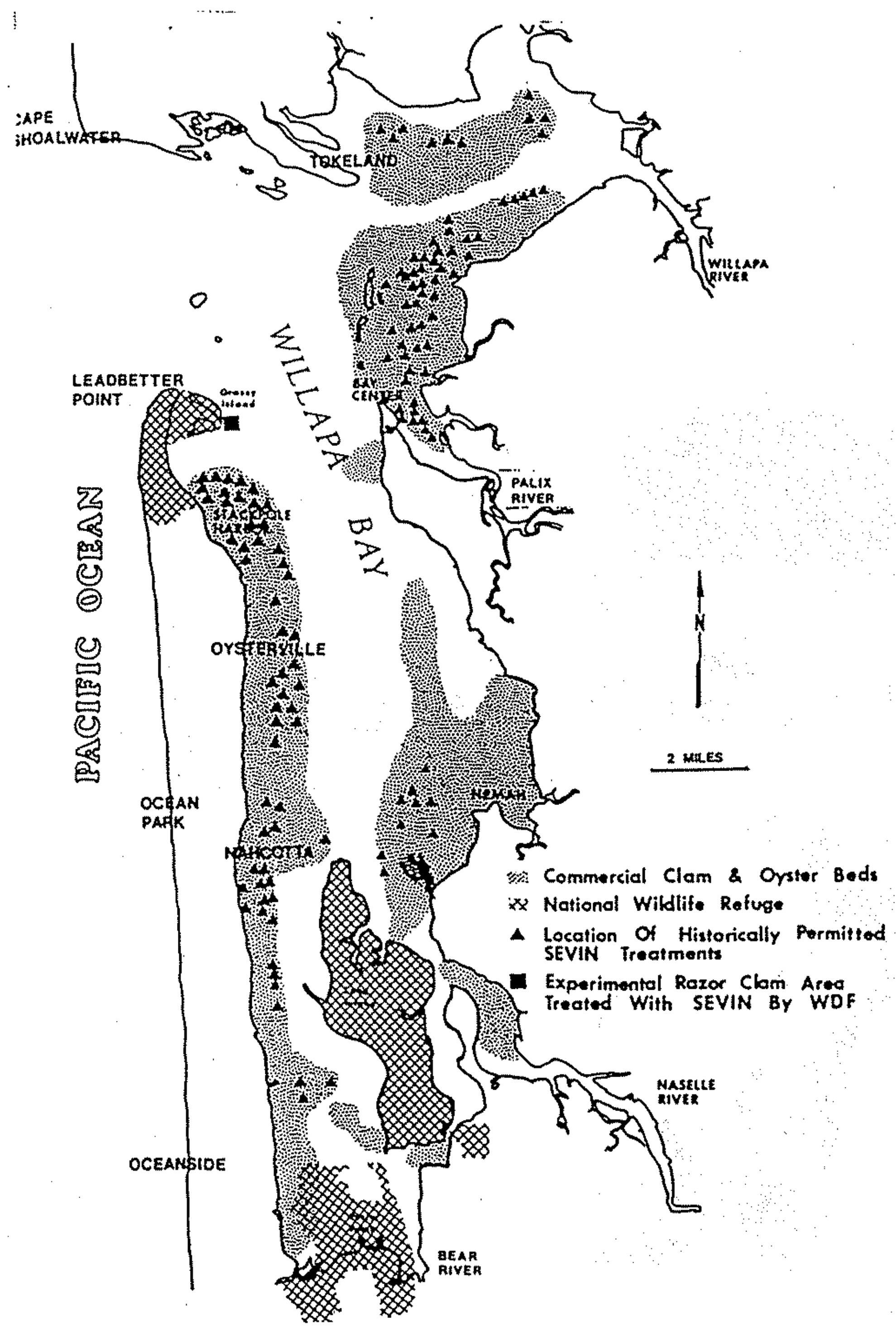


Figure 5.6 Areas of oyster culture in Willapa Bay (WDOE 1983).

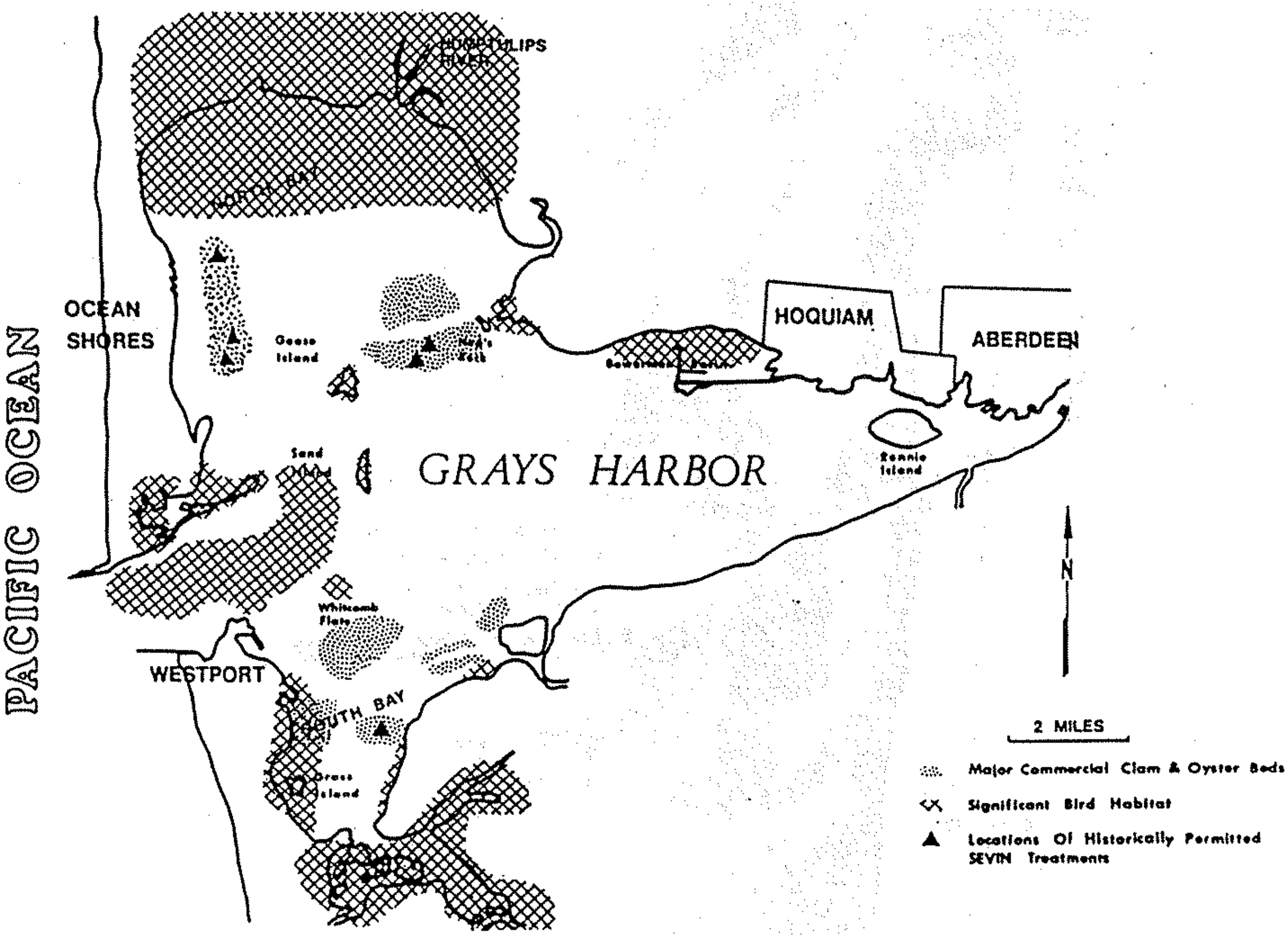


Figure 5.7 Areas of oyster culture in Grays Harbor (WDOE 1983).

6.0 METHODS OF REDUCING DAMAGE FROM BURROWING SHRIMP

A wide variety of methods have been proposed to control burrowing shrimp or minimize the impact they have on oyster farming, including chemical, physical, and biological controls and changes in cultural practices. As we were specifically directed not to conduct field or laboratory research, data gathering for our evaluation of existing methods was limited to surveys, interviews, reviews of recent research, and our own experience. In this chapter, we evaluate several methods to manage burrowing shrimp that have been tried by oyster growers in Willapa Bay and Grays Harbor, and we suggest possible combinations or modifications of existing methods that might be explored by growers in the future. A benefit-cost approach to evaluate new control methods is presented in Appendix C.

Fifteen methods for managing burrowing shrimp are outlined in Table 6.1. This list was formed through discussions with members of the Burrowing Shrimp IPM Oversight Committee, oyster growers, and estuarine ecologists. Oyster growers in Willapa Bay and Grays Harbor have tried many of these methods, notably carbaryl pesticide, sediment barriers, substrate compaction, clay injection, shell or gravel paving, harrowing, water jets, electro-shocking, floating culture, and harvesting burrowing shrimp. Relatively few scientific studies have been conducted to evaluate the efficacy or practicality of many of these methods, although research has been conducted to evaluate carbaryl pesticide, other pesticides, predation, shell paving, reinforcement of longline structures, and alternative crops.

Based on discussions with growers and experts, and on our own evaluations, six other methods were considered to be technically unfeasible or impractical. These were development of silt-resistant oysters, release of parasites and pathogens of shrimp, release of sterile male shrimp, bioengineering faulty genes into the burrowing shrimp population, use of explosives, and use of floating culture growing methods.

- Development of silt-resistant oysters is technically unfeasible. Such an oyster would have to somehow avoid burial of sediment resuspended by burrowing shrimp by shedding sediment from its upper valve or moving upwards through sediment. Both mechanisms are currently impossible because oysters are sessile and cannot grow sufficiently fast to avoid burial.
- Use of explosives to control burrowing shrimp is considered impractical and unacceptable in that explosives are costly, could damage the oyster crop, and could adversely affect other estuarine organisms (including fish, birds, and marine mammals).

- The release of pathogens or genetically altered shrimp to control burrowing shrimp is both impractical and ethically questionable. Virtually nothing is known about burrowing shrimp-specific diseases, parasites, or genetics; release of such agents would likely affect populations outside of oyster grounds and outside of the estuaries. Even though ghost shrimp and mud shrimp appear to have undergone population explosions and are pests to oyster farming, they are an indigenous species, a normal part of the ecosystem, and are important components to benthic communities. The use of diseases, parasites, or modified shrimp would be irresponsible without full understanding of the consequences.
- Floating culture is not a practical method for growing oysters in Willapa Bay and Grays Harbor. As was discussed in Chapter 3, floating culture can be a productive way to raise oysters, but requires deep waters outside of navigation channels (which are scarce in these two estuaries). Also, the floating structures are quite vulnerable to damage from storms.

Thus, we have excluded these six methods from further evaluation.

6.1 CHEMICAL CONTROL METHODS

Chemical controls are typically pesticides that disrupt metabolic, neurological, developmental, endocrine, or reproductive functions within the target organism. Chemical controls are usually the fastest acting and least expensive control methods in agriculture, as is also true for the control of burrowing shrimp. At this time, the pesticide carbaryl has been the only dependable and economically feasible method to control burrowing shrimp in Willapa Bay and Grays Harbor.

6.1.1 Carbaryl Pesticide. Historically, the use of chemical pesticides for the control of thalassinid burrowing shrimp in the coastal estuaries of Washington state began in 1963 with the use of carbaryl, (trade name, Sevin) (WDF 1970). This carbamate compound was brought into use through the work of Dr. Victor Loosanoff, who in the late 1950s selected carbaryl as the most suitable among the chemical alternatives available at that time for screening (WDF/WDOE 1985; L. Weigart, pers. comm.). Since that time, carbaryl has remained the sole chemical control and the principle method used against burrowing shrimp. The Washington Department of Ecology authorizes and regulates the use of carbaryl under WAC 220-20-10(16) in compliance with the Washington State Special Local Needs Pesticide Registration No. WA760021 under authority of section 24(c) of the Amended Federal Insecticide, Fungicide, and

Rodenticide Act. This program is the only reported commercial use of chemicals to control thalassinid shrimp as pests (Dumbauld et al. 1996).

Current practice involves helicopter application of Sevin 80WP (wettable powder) to oyster beds at low tide when wind velocity is less than 10 mph at the rate of up to 11 lb formulated material with 10 gallons of water per acre. Although lower application rates have proven to be effective in small-scale experiments when exposure periods were long (Dumbauld 1994), lower rates have not provided satisfactory control under some full-scale, commercial-scale operations (D. Tufts and R. Wilson, pers. comm.). Up to 800 acres per year are treated under a seasonal permit process administered by WDOE. A threshold of 10 shrimp burrows per square meter is used in the determination of the need for control in a given oyster bed (WDF/WDOE 1992). Spraying is conducted in mid-summer when salmonid migration is at a minimum and during Spring low tides so that the tideflats are maximally exposed during daylight. Based on need, growers would treat more acreage and at an earlier timing if it were permitted (R. Wilson, pers. comm.).

Carbaryl (1-naphthol n-methyl carbamate), in the powder form, is crystalline in particle structure and ranges from 3 to 40 microns in size. A relatively low water solubility (0.005 g/100 g water at 20°C) renders the delivery of toxicant to the target organism to be essentially limited to individual particles drifting into individual shrimp burrows, whereby through burrow ventilation, ghost and mud shrimp draw the chemical into their burrows and are exposed to a sufficient dosage of particles to cause mortality. Control efficacy is evident within 5 minutes following aerial application by the emergence of dying mud shrimp onto the sediment surface (T. DeWitt and T. Wildman, pers. obs.).

Carbaryl and its breakdown product, 1-naphthol, have been shown to have been transported short distances from the application site. Depending on environmental conditions, carbaryl and 1-naphthol may persist for a few days (in water) to several weeks (in sediments) at levels near the lower limits of detection. Data published in WDF/WDOE (1985, 1992) show that carbaryl residues from summer applications degrade rapidly. Carbamates are not known to bioaccumulate in the food chain (WDF/WDOE 1992).

Carbaryl, a synthetic auxin analog, has no known effects on aquatic plants. The LC50 for various invertebrates ranges from 0.03 ppm to 7.3 ppm (WDF/WDOE 1992). Carbaryl has significant short-term impacts on the abundance and diversity of benthic invertebrates

(Dumbauld 1994; Brooks 1995). However, recolonization of treated beds by many invertebrates begins within 24 hours. No long-term adverse effects to estuarine communities (including benthic invertebrate communities) have been clearly attributed to carbaryl application, with the exception of the eradication of burrowing shrimp (WDF/WDOE 1992; Brooks 1995; Simenstad and Fresh 1995). In fact, a long-term consequence of controlling burrowing shrimp densities on oyster beds using carbaryl has been the increase in benthic invertebrate species diversity, growth of eelgrass, and increase in Dungeness crab abundance (Doty et al. 1990; Brooks 1995; B. Dumbauld, pers. comm.). Dungeness crabs, which are highly susceptible to carbaryl, may not recolonize treated oyster beds for up to 2 weeks, but afterward can attain higher abundances than on tide flats with high burrowing shrimp densities (Doty et al. 1990). The LC50 of carbaryl to finfish is in the range of 5 ppm to 13 ppm, and fish trapped in pools of water on the tide flat are often killed following a carbaryl application (WDF/WDOE 1992). Mammals and birds show no sensitivity to carbaryl at several orders of magnitude above the range of toxicity to fish and invertebrates. No adverse effects have been observed to birds feeding on dead shrimp in carbaryl treated areas (WDF/WDOE 1992). A comprehensive treatment the environmental degradation and toxicity of carbaryl is presented in WDF/WDOE (1985 and 1992).

6.1.2 Possible Changes to Carbaryl Application. The current practice for commercial application of carbaryl is by helicopter for large plots (≥0.5 acre) and by hand for small plots. Ground equipment fitted for application of toxicant may have some advantages. Larger volumes of more dilute concentrations may be delivered to the application site, possibly enhancing efficacy by delivering more material into shrimp burrows. Off-site spray drift would be minimized if more precise application methods were used. Spray nozzles and shank injection are two possible pesticide-delivery devices. The use of shanks to inject toxicant into the sediment below the surface has been investigated with positive results (J. Durfey, pers. comm.). This method of application would minimize the potential for offsite pesticide drift. More work should be done to evaluate the potential of ground, as opposed to aerial, pesticide application. Controlled experiments using various ground equipment, such as swamp or tundra buggies fitted with spray tanks and nozzles or shank injector systems, should be conducted. A potential drawback may be the limited time in which pesticide applications are permitted relative to the area to be treated. Suitable ground application equipment would likely be limited in weight and size, and therefore pesticide load carrying capacity would be limited proportionately.

Border treatment is reported to have been effective at preventing shrimp movement before the onset of the previous El Niño event (L. Bennett, pers. obs.). Once shrimp control is achieved in large areas of contiguous oyster beds, border spraying or shank application may significantly hinder and slow lateral movement of large burrowing shrimp back into the oyster beds.

Adaptation of a ground delivery method would likely require several days of effort (over multiple low-tide series) or use of several vehicles to enable growers to cover the ground needing treatment within the time frame allowed under the permit process. If it were demonstrated that such applications were inherently of less risk to fish and other organisms in the estuarine community, the time frame of permitted applications may be altered so that the acreage in need of shrimp control could be treated at various low tide sequences during the period when shrimp are most active.

The timing of carbaryl application is currently established for mid-summer to minimize exposure of migrating salmonids to the pesticide. Mid-summer is also when the lowest daytime tides occur, exposing more tideflats for aerial spraying during daylight hours than at any other time of year. Growers and biologists have suggested that, if carbaryl treatment were permitted in the fall, the pesticide could be applied shortly after ghost shrimp recruit into oyster beds (typically, November) (Dumbauld et al. 1996). By eliminating the recruiting year-class, ghost shrimp population growth rate would probably be slowed sufficiently that the oyster beds could go at least one year longer between treatments. However, water and air temperatures would be colder, thus reducing the efficacy and decomposition rate of carbaryl, and the lowest tides would occur at night, possibly hindering application of the pesticide to lower intertidal oyster beds. To our knowledge, no studies have evaluated the efficacy or risks of carbaryl application at times of year other than mid-summer. Additional studies should be conducted before the timing of carbaryl application is changed.

6.1.3 Other Pesticides. An IPM plan that uses a chemical control component can benefit from the availability of a variety of chemicals from which to chose. Dependence on a single chemical for pest control may render the IPM plan unstable, particularly if the pesticide is a dominant component of the suite of control tactics, as is currently the case in oyster culture. New classes of pesticides may be developed that have desirable properties (such as lower non-target toxicity, different means of application, or different modes of toxicity) that would make them candidates for supplementing or replacing current pesticides. Additionally, the sudden cancellation of the only available chemical control, or other mitigating regulatory action, would effectively remove that control tactic. Growers we interviewed felt that oyster culture in Willapa Bay and Grays Harbor would become economically unfeasible at the scales now farmed if carbaryl were made unavailable and no alternative was present. Therefore a program to identify and test appropriate alternative chemical controls should be employed, in addition to efforts to develop cultural, physical, biological, and other control measures.

Choice of candidate chemicals should take into consideration the status of the pest population, (i.e., stasis, outbreak, chemical resistance, developmental stage), toxicity to non-target resources, and various environmental parameters that affect the application, efficacy, and environmental fate of the compound. As a beginning point, candidate compounds should have high toxicological specificity to arthropods, negligible toxicity to vertebrates (especially fish, birds, and mammals), oysters, and plants, and rapid degradation into harmless components. A 10-fold lower non-target toxicity than carbaryl would be a reasonable initial target. Most can be generally classified as either neurotoxins or growth regulators. Access to alternative compounds with different modes of action and different effects on both target and non-target organisms would allow growers more opportunities to tailor their pest control actions, which could result in chemical-use patterns that reduce the total amount of pesticide used on a crop.

Driven by the need to protect the environment and meet pest control needs in the face of removal of older pesticides from the marketplace, agri-chemical manufacturers are developing new generation pesticides with novel modes of action and greater specificity against target organisms (Moffat 1993). Some of the new neurotoxins are active on neurotransmitters not found in mammals, birds, and fish. Growth regulators generally function to inhibit or alter the molting and/or reproductive processes of select groups of arthropods. Modes of action of these compounds include juvenile hormone analogs, ecdysone agonists, and chitin inhibitors. Terrestrial agricultural industries are currently funding research programs toward the registration of these compounds. Several alternative compounds (with novel modes of action and selective toxicities) are now available for testing, and it seems reasonable to conduct efficacy studies to determine whether these compounds might be appropriate for controlling burrowing shrimp.

A multi-phase approach should be followed to select candidate compounds: 1) review technical literature to identify candidates, 2) compare efficacy of candidates against the pest through field trials, and 3) measure target and non-target toxicity in laboratory experiments to fulfill the pre-registration requirements of regulatory agencies.

The initial phase of selection of candidate pesticides is to consider the toxicological mode of action. The nervous and endocrine systems are largely homologous within the Arthropod phylum (Barnes 1980), and a reasonable first-order assumption is that shrimp share many of the toxicological susceptibilities of insects. Therefore, compounds shown to be effective against insect pests in terrestrial agricultural systems may also be toxic to burrowing shrimp. The sensitivity of burrowing shrimp to carbaryl demonstrates their vulnerability to acetylcholine esterase-inhibiting neurotoxins. The majority of older generation World War II era insecticides have this mode of action in common. However, animals from many phyla share that aspect of neural physiology, which is why carbaryl, most other carbamates, and several other insecticide classes (such as organo phosphates, organo chlorines, and pyrethroids) are non-selective in their toxicities. For these reasons, non-selective pesticides are generally less compatible with objectives of IPM than are more selective compounds (T. Wildman, pers. obs.).

Pesticide manufacturers will provide some of the technical data on the critical properties of pesticides, whether registered or under development. However, detailed toxicological and environmental fate information can be considered to be proprietary by the company and, therefore, difficult to obtain. The public is usually limited to published results of research conducted by second parties (i.e., government laboratories, universities, non-government agencies), much of which is funded either by agricultural industries or government regulatory agencies. Publically accessible information can include toxicities of the compounds to a range of standard test organisms that represent many of the common classes of animal life. In the aquatic environment (including estuarine and marine environments), this typically includes arthropods (insects, daphnids, mysid shrimp, amphipods), molluscs, echinoderms, fish, and occasionally, annelid worms and plants. These reports provide crucial information to evaluate the potential toxicity of the compound to the pest and to non-target natural resources.

The second phase of work involves field trials of candidate compound(s) at different application rates to the target organism within the agricultural setting. These trials should be conducted using a statistically rigorous experimental design so that treatment effects (i.e., individual chemicals, application rates, and controls) can be differentiated from environmental factors (i.e., physical and chemical properties of the site, site-specific peculiarities in the behavior or ecology of the pest population, or unexpected factors that affect the health of the pest). Real time monitoring of environmental parameters, including sediment and water-column pesticide burden and non-target organism mortality, should also be conducted both within and adjacent to experimental plots.

An additional consideration for alternative chemical control compounds is the precision of the application method, such as ground application versus aerial application. Ground application of pesticides usually is more precise in the spatial distribution of the compound, and potentially can be targeted directly to the site of the pest, thus reducing the amount of pesticide that needs to be applied and minimizing the potential for off-site drift of the chemical. In combination with greater selectivity in toxicity, increasing the precision of the application of the pesticide can further minimize negative impacts to the environment.

6.1.4 Progress-to-Date on Selection and Field Testing of Other Pesticides. A project led by Alan Schreiber (Washington State University Department of Entomology) and Tedd Wildman (Independent Pest Management), with assistance from Dennis Tufts (E. H. Bendikson Company) and Brett Dumbauld (Department of Fisheries and Wildlife) was initiated in 1996 to investigate alternative chemical control tactics. As of May, 1997, two trials of the study had been completed, and results from that study are presented in Appendix D. Briefly, in their first trial, Schreiber and Wildman found that abamectin and imidacloprid were capable of controlling burrowing shrimp. However, inclusive results were obtained from the second trial. Chemistry data and the proximity of recently treated oyster beds suggested that carbaryl from an outside source entered the second-trial study area, contaminated the water or sediment, caused a wide-spread reduction in burrowing shrimp populations throughout the study site, and thereby interfered with the field trial. Thus, the cost-effective application rate and volume of abamectin and imidacloprid remain uncertain. Additional field trials are planned for the summer of 1997 to evaluate the application rates for these pesticides.

6.1.5 Considerations for Developing Other Pesticides. In order to proceed with the development of a cost-effective, reduced-risk pesticide for control of burrowing shrimp, the following must occur: 1) a cost-effective application rate must be determined, 2) the manufacturer must agree to allow its product to be registered for this use, 3) state regulatory agencies must support the registration effort, 4) additional data on the toxicity, use pattern, and environmental fate of the chemical must be collected, and 5) there must be support from EPA, WDOE, and other resource agencies to allow registration of the product. The status of abamectin and imidacloprid from these perspectives are:

- *Cost-effective application rate.* A gallon of imidacloprid costs $496. A gallon of abamectin costs $667. At a rate of 0.25 lbs to 1.0 lbs of active ingredient per acre, the cost to treat one acre of oyster bed with imidacloprid would be $77 to $310. At a rate of 0.06 lbs to 0.2 lbs of active ingredient per acre, the cost to treat one acre of oyster bed with abamectin would be $267 to $889. According to growers (R. Wilson and D. Tufts, pers. comm.), the highest application rates of abamectin and imidacloprid tested by Schreiber and Wildman were too high to be cost-effective. It is possible that a use pattern with a lower and more economical rate of application could be developed that would control burrowing shrimp. In addition to being more cost effective, a lower application rate could have reduced impacts on non-target species. Therefore, additional work is necessary to develop a more practical use pattern with the alternative control materials. Additional trials should include collection of more extensive environmental data on the fate and off-target movement of treatment chemicals. Inclusion of an environmental toxicologist on the team of investigators could provide insight into potential environmental impacts of the treatment compounds.

- *Manufacturer support.* Obtaining manufacturer support will be difficult. The manufacturer's first response to the question of whether it would allow abamectin to be registered was a definitive "no." It was the belief of company representatives that EPA would never allow it. Upon further discussion, a representative of the manufacturer stated that it might be willing to entertain a registration if the following conditions were met:

  1) EPA and other resource agencies provide some indication that they would be willing to consider registration of the product,
  2) a third party assumes both the registration and liability associated with the product's use, and
  3) the cost of developing the data would not be the responsibility of the company.

- *State resource agencies.* As the state lead agency for pesticides, the Washington State Department of Agriculture must permit registration of any alternative chemical use pattern. This would require extensive further data on efficacy, evidence of special local need under FIFRA Section 24(c), a registrant willing to register the product, and evidence that no unreasonable risk to humans or the environment would result. The Washington Department of Ecology and the Department of Fish and Wildlife would also have to allow the registration to proceed. Assuming a registrant would allow registration of the product, the primary obstacle would be establishing that the risk to the environment is not unreasonable or is at least acceptable.

- *EPA*. Historically, EPA has been reluctant to register any insecticides for use near or in aquatic habitats. Abamectin is currently under EPA scrutiny because of concerns about impacts to aquatic organisms. If an alternative to carbaryl is to be developed and used by growers, it would require registration under the Federal Insecticide, Fungicide and Rodenticide Act by the EPA Office of Pesticide Programs. Sufficient justification for registration of abamectin, imidacloprid, or another compound may be found if it were demonstrated to be a less toxic alternative to the current control alternative, and if this led to an overall decrease in use of pesticides in the estuary. State agency support from the WSDA, WDOE and WDFW, would be required to obtain EPA approval. EPA would also require numerous data on the non-target toxicity and environmental fate of the compound prior to making a decision whether to allow registration. The cost of pursuing a registration would probably require financial resources beyond those available from the oyster growing community. It is possible such support could come from the state or from growers and agencies in adjacent states that also have problems with burrowing shrimp on oyster ground.

Whereas research on these pesticide alternatives to carbaryl is still underway, and many regulatory requirements must be met before they can possibly be used legitimately, we cannot presently recommend their use for controlling burrowing shrimp on commercial oyster beds.

6.2 Biological Control Methods

Biological control methods include predators, competitors, parasites, disease vectors, and bioengineered "drones" (i.e., sterile males or fertile males with defective genes). Enhancement of natural enemies of pests can be useful for slowing the population growth rate of pests, but is not likely to entirely eradicate a pest. At present, there is relatively little known about the efficacy of biological controls for burrowing shrimp, with the exception of predation, and knowledge about that is limited. As discussed previously, parasites and bioengineered shrimp have been proposed, but as almost nothing is known about candidates for the former or the genetics of callianassid shrimp, and as we considered the costs to develop such knowledge to be prohibitive, these proposals were not evaluated further.

6.2.1 Predator Enhancement. As described in the Chapter 4, at least four estuarine aquatic species are known to feed on ghost or mud shrimp: staghorn sculpin, cutthroat trout, white sturgeon, and Dungeness crabs. Other species opportunistically feed on adult and larval burrowing shrimp, but these four are the best known predators of YOY and adult shrimp.

At this time, there is no known method for enhancing predator populations in a manner that would indisputably reduce, let alone control, burrowing shrimp populations. However, this is an area in which additional research would be beneficial in that enhancement of natural populations of native fish species in these estuaries is desired by many sectors of the greater Willapa-Grays Harbor community (Alan Lebovitz, Willapa Alliance, pers. comm.). Below we suggest some possible approaches to enhancing populations of burrowing shrimp predators. However, these approaches are speculative.

One approach to enhancing predation by fishes is to increase the abundance of fish. This can be accomplished by reducing mortality, enhancing reproduction, enhancing recruitment, and enhancing immigration or reducing emigration. None of these steps are trivial, and most require the participation and cooperation of other citizens, commercial interests, and agencies living and operating in the region. Reduction of mortality of cutthroat trout and sturgeon might be accomplished through reduction in fishing pressure, such as reducing the existing catch limit or fishing seasons.

Another approach to enhancing populations of shrimp predators could be to provide habitat features for these species that provide protection from their predators. Eelgrass beds may serve this purpose for many species of fish, including sculpin, sturgeon, and juvenile salmonids. However, dense beds of eelgrass can interfere with certain aspects of oyster farming, particularly mechanical harvesting on bottom culture. Research is needed to determine whether these practices truly harm eelgrass beds, and what modifications to machinery and culture methods can be developed to minimize any adverse impacts. If others value eelgrass beds on oyster farmers' private property, then agencies should find resources and incentives to encourage oyster farmers to enhance those beds. Possibilities include research to develop new tools and machinery for oyster farming, property trading, tax incentives, and impact trading. Further analysis of this issue is outside the responsibility of this study.

Enhancement of reproduction of predatory salmonids might be accomplished through support of conservation activities that restore and protect salmonid and sturgeon breeding habitat. Cutthroat breeding habitat occurs in the tributaries of Willapa Bay and Grays Harbor estuaries, but white sturgeon apparently do not breed locally. Based on tagging studies, white sturgeon from the lower Columbia River migrate to coastal estuaries of Oregon and Washington, but do not reproduce there (Steve King, Oregon Department of Fish and Wildlife [ODFW], and Brad James, pers. comm.). As Washington State has no plans for creating a sturgeon hatchery in the Willapa Bay or Grays Harbor watersheds, growers' best chance to enhance sturgeon populations would be to support WDFW and ODFW sturgeon enhancement programs for the lower Columbia River. We were unable to determine what steps could be taken to enhance the reproduction of staghorn sculpin. Enhancing immigration or reducing emigration of any of the fish might be achieved by increasing the amount of habitat each species requires (foraging area, refuge, breeding area). Use of an attractant (such as a reproductive pheromone) might temporarily increase the local abundance of the fish, but without an incentive to remain, the fish would probably leave as soon as the attractant dissipated or the fish habituated to it. Habitat features that might be attractive to these species include eelgrass, cracks and crevices (for sculpin especially), and deep water (for sturgeon).

Related to this, and on the scale of oyster beds, growers might be able to provide fish with the means to occupy intertidal habitat at low tide. Posey (1986b) found that predation by staghorn sculpin was largely responsible for controlling the depth distribution of ghost shrimp. Ghost shrimp living in the upper portions of the intertidal, however, were protected from predation because the fish could only feed when the flat was covered by water. If oyster beds were diked or dammed to retain water at low tide, fish trapped or placed in the pools would have a longer period to forage for burrowing shrimp. This would probably work best for the diminutive staghorn sculpin, because they would not require as deep of pools as other species. Getting fish to stay on the beds would be another challenge. It might be possible to add features to the oyster beds to make them more attractive, for example, structures for shelter or reproduction. Alternatively, growers might try to trap the fish on the beds using weirs, nets, or fences, though these would have to be fairly fine mesh (~2-cm diameter or less) to retain the sculpins. Again, these ideas are speculative and untested.

Predation by Dungeness crabs and related species on YOY burrowing shrimp may help reduce the growth rate of the pest populations on oyster beds. As described in Chapter 4, YOY Dungeness crabs on shell substrates prey on recruiting YOY ghost shrimp, and even show a preference for the shrimp over several other benthic organisms. Although Dungeness crabs also prey on YOY mud shrimp, crab predation seems to be less effective at controlling mud shrimp than ghost shrimp. This largely may be caused by the coincidence of mud shrimp and Dungeness crab recruitment (in spring), which results in an abundance of juvenile crabs that may be too small to prey on the mud shrimp. Nonetheless, crab predation can be effective at reducing the success of ghost shrimp recruitment. Crabs are attracted to physical structure, such as oyster clusters and eelgrass, which they can use as refugia from their predators (Doty et al. 1990). Enhancement of the abundance of YOY Dungeness crabs might be achieved by increasing habitat features that attract recruiting crabs. This includes eelgrass and physical structures, such as oyster shell. Use of shell pavement on oyster beds (described below) will attract YOY crabs, as will clusters of mature oysters.

Note that physical modification of tideflats (i.e., diking, daming, shell pavement) to create habitat for burrowing shrimp predators could have unexpected affects for other benthic resources, and that few of these methods have been tried previously. These ideas are presented only as suggestions for future investigation.

6.3 Physical Control Methods

Physical methods to control pests include habitat alterations that are inimical to the pest and use of machinery to either kill the pest or force it to leave the area. Some of the proposed physical controls are modifications of activities that are conducted in order to grow or harvest oysters; other methods are specifically designed to target burrowing shrimp. Oyster farmers in the Willapa-Grays Harbor estuaries have tried several of these methods at various times since the 1950's, and at various spatial scales; none have yet proved effective. Furthermore, these physical methods can alter tideflats habitats in manners that may be adverse to the farming of oysters or to populations of other benthic organisms. Unfortunately, little actual data has been collected with which to make objective or complete evaluations of the efficacy or impacts of most of these methods.

6.3.1 Sediment Barriers. Placement of a material impenetrable to shrimp on top or just under the surface of the oyster bed will reduce or effectively eliminate damage from shrimp for a period of time. The first documented use of shrimp sediment occlusion barriers is from the oyster farming operations on the Olympic Peninsula in the early 1910s (Steele 1957). At that time, dikes were used to create impoundments to facilitate oyster growing. Burrowing shrimp (called "crawfish" by Steele) caused damage by their direct effect on the oyster bed and by causing dike failure. Shrimp burrows under and through dikes caused the walls to wash out, resulting in extensive economic damage. The problem was "solved" by covering the oyster bed with lumber or plywood and covering that with a layer of gravel. Barrier materials that have been tried more recently include porous fiber mats and sediment barriers.

Contemporary growers report variable success with these techniques. Growers in Willapa Bay report unsuccessful results and deleterious impacts with experiments using barriers laid over the sediment surface to prevent shrimp colonization and burrowing (L. Weigart, pers. comm.). An impermeable sediment barrier will smother not only burrowing shrimp, but also other benthic invertebrates beneath the sheet. In addition, oysters placed directly on top of the sheet are easily moved by currents and waves to piles along the edges of the sheets, which causes reduced growth in those oysters at the bottom of the heap. Tidal action and storm surges dislodge and shred the sheeting, creating a debris problem as well. The practice is not currently employed there.

In Puget Sound, growers report success using a semi-permeable fiber mat (trade name, Geotech) on seed beds to control burrowing shrimp. Costs may be as high as $11,000/acre, with 50% of that being labor (P. Taylor, pers. comm.). Experience has shown that gravel deposited on the mat at a depth of 6 in. yields better results than if sediment is layered over the mat. If gravel must be trucked to the site, costs are higher. This barrier must be able to work effectively for several years in order to justify its cost. To our knowledge, this method has not been tested in Willapa Bay or Grays Harbor, but it would seem that exploratory trials would be worthwhile. If this method were to be tested, its ability to withstand storm currents, waves, and associated sediment transport must be demonstrated. However, as this method has not been tried yet in Willapa Bay or Grays Harbor, nor have its impacts on other estuarine species been investigated, we cannot presently recommend its use as proven method for controlling burrowing shrimp on commercial oyster beds.

6.3.2 Sediment Compaction. Sediment compaction, often referred to as "rolling" by oyster growers, has a long history of trial use dating back to the 1950's (L. Weigart, pers. comm.). The use and mode of action is to drive or drag a heavy object (i.e., wheel, roller, or sled) across the sediment surface that will cause the shrimp's burrows to collapse, and either crush, smother, or force the shrimp to dig its way up to the sediment surface, where it dies from exposure, predation by birds, or harvesting by the growers. Sediment compaction is limited to use on fallow beds for obvious reasons: the equipment that compacts the sediment would also damage or bury oysters. A wide variety of heavy machinery has been tried for this purpose, including bulldozers, amphibious vehicles (WW II surplus), rollers, and sleds. Rolligon™ tractors and swamp/tundra buggies are other examples of equipment previously employed. Lighter equipment tends to form a crust on the sediment surface. The addition of a pulled roller was reported to produce better results (L. Weigart, pers. comm.). There are reports of heavy equipment lost in the sediment during previous efforts, at present still buried somewhere in the tidal flats.

Growers report that the short-term effects of compaction on the oyster beds can be positive, albeit with mixed results. Although there is some initial shrimp mortality and sediments are temporarily compacted, most shrimp are simply forced from their burrows, survive, and subsequently dig new burrows. The consistency of the bed soon returns to the previous state. Effects on other benthic invertebrates are poorly understood at this time, but are likely to include short-term decrease in abundance, followed by re-colonization and increased biodiversity (relative to oyster beds with high densities of ghost shrimp).

Vibrating equipment used commercially to settle freshly poured concrete has also been employed experimentally by growers (L. Bennett, pers. obs.). The practice is laborious, time consuming, and costly. Results were positive, but shrimp tended to move back into the compacted area after a relatively short period of time.

Further investigations under controlled experimental conditions should be pursued. The rate and extent of recolonization by burrowing shrimp should be measured, as well as the effects on non-target species, particularly eelgrass and benthic invertebrates. Methods of killing or harvesting shrimp that have emerged from their burrows would likely increase the efficacy of compaction as a method of shrimp control.

6.3.3 Dredge Harvest of Oysters. Studies were conducted in 1996 in Grays Harbor to determine whether mechanical dredge harvest of bottom-cultured oysters could either kill YOY ghost shrimp residing near the sediment surface directly (by crushing) or indirectly when the shrimp were brought to the sediment surface and exposed to predators (K. Feldman, B. Dumbauld, and D. Armstrong, unpubl. data). In an experiment conducted during the spring, ghost shrimp on the mature oyster bed were unaffected by dredging, but densities of shrimp on a fallow bed were significantly reduced. The opposite pattern was observed in the fall: after dredging, YOY ghost shrimp densities were significantly reduced on an oyster bed but not on a fallow bed. The presence of a dredging effect in the spring but not in the fall on the fallow bed may have been caused by differences in the seasonal abundance of predators and proximity of the shrimp to the sediment surface. With respect to the mature oyster bed, the researchers determined that the reduction of ghost shrimp in the fall was more likely caused by natural mortality rather than by dredging. In summary, the physical disruption of the benthos resulting from oyster dredging might have some application for YOY shrimp control, particularly if growers were to dredge fallow beds in the spring prior to planting oyster seed. Additional studies are needed to evaluate the effectiveness of method to control newly settled burrowing shrimp before a recommendation can be made as to its utility on a commercial basis. Although dredging shows some promise as a control method, it may have unintended affects on other estuarine species, and we cannot recommend it as a proven method to control burrowing shrimp at this time.

6.3.4 Harrowing. As with dredge-harvesting of oysters, harrowing is a combination of a cultural method and a physical control method. Spring-tined English harrows are used in bottom culture to prepare beds for harvesting. At high tide, the implement is dragged across the oyster bed by boat, and in the process, oysters are lifted from the sediment so as to facilitate harvest. It has been suggested that by physically lifting oysters from the sediment, periodic harrowing may lessen the negative effects of substrate destabilization caused by shrimp. However, harrowing also loosens the sediment surface, which can cause oysters to sink into the substrate where they may be smothered (L. Bennett, pers. obs.). Thus, once started, harrowing conducted substantially before harvest may require periodic re-harrowing just to mitigate the effects of the harrowing on the oysters. Therefore, harrowing is usually conducted just prior to harvest, or it could be practiced when oysters are not on the ground. It has been suggested that harrowing might kill or damage shrimp by causing burrows to collapse or by impaling or cutting through the bodies of the shrimp.

No scientific studies have been conducted to evaluate the efficacy of harrowing. However, many bottom-culture oyster growers harrow oyster beds prior to harvest and have had considerable opportunity to subjectively evaluate its effects on burrowing shrimp densities. Oyster growers report that burrowing shrimp are relatively unaffected by the harrow (L. Bennett, pers. obs.; R. Wilson, pers. comm.). Therefore, the oysters pulled up from the sediment simply settle back into the destabilized oyster bed and resume sinking or being buried by the activity of the shrimp. Furthermore, harrowing increases water turbidity and loosens the substrate, which can also harm the oysters. Harrowing as a physical means of controlling shrimp or circumventing damage caused by shrimp is deemed to be of extremely limited utility. Furthermore, if used frequently on oyster beds before the crop is harvestable, the practice may have additional negative impacts on oyster growth and development.

The use of disking and plowing equipment as commonly used in terrestrial land cultivation has been tried as well (L. Bennett, pers. comm.), with similar results as harrowing. Shrimp burrow densities can be temporarily reduced by 25% to 50%, but soon regain their former abundance. This suggests that either new shrimp colonize the sediments or the shrimp are not killed and just excavate new burrows. The latter case is quite likely to occur, because the tines of the harrow typically penetrate only a few inches into the substrate, whereas burrowing shrimp can retreat two feet below the sediment surface to the bottom of their burrows. In addition, recovery of a bed after disking and plowing requires a longer period of time than is compatible with oyster culture.

As currently practiced, harrowing or disking appear to be ineffective means of controlling burrowing shrimp. However, it is possible that harrowing or disking might be more effective on young of the year (YOY) shrimp than on older shrimp: newly settled recruits build shallow burrows and might be more vulnerable to disturbance of the sediment surface and to exposure to predators. If YOY shrimp are forced to the sediment surface, some means of collecting or killing them could be employed to increase the efficacy of harrowing and to help slow the burrowing shrimp population growth rate. This is a topic that could be investigated for relatively little cost at different times of year, on different substrates, and in different locations.

Many of these ideas are speculative and unproven as effective means to control burrowing shrimp, and may have unintended affects on other estuarine species living on, or using the tideflats. Thus, we can not recommend use of harrowing as a proven method to control burrowing shrimp at this time.

6.3.5 Clay Injection. Some growers have conducted small-scale experiments pouring or injecting bentonite clay into shrimp burrows with the thought that the clay would clog the water-filtering or respiratory activity of the shrimp, thus smothering them (L. Bennett, pers. obs.). These growers reported that, in most cases, burrowing shrimp pumped the clay out of the burrows and apparently suffered little damage. Growers were unsure how this method could be applied on a commercial-bed scale. For now, clay injection appears to be an impractical and ineffective control method, and does not appear to merit further study.

6.3.6 Oyster Shell "Pavement". Experiments are currently being conducted by D. Armstrong, K. Feldman (Univ. Washington, School of Fisheries) and B. Dumbauld (WDFW) to investigate whether oyster shell, distributed as a thick "pavement," might stabilize and compact intertidal sediments and thus serve as a foundation for bottom-culture of oysters while creating habitat unsuitable for burrowing shrimp. Replicated plots have been established at two sites in Willapa Bay, one dominated by ghost shrimp (Nahcotta) and the other by mud shrimp (Cedar River). Treatments consist of plots sprayed with carbaryl ("treated"), plots sprayed with carbaryl and subsequently shelled ("treated + shell"), plots shelled without carbaryl treatment ("untreated + shell"), and plots left untreated to serve as controls ("untreated"). The effect of carbaryl application was to eliminate existing shrimp from these treatments ("treated" and "treated + shell"), but retain shrimp on those treatments not sprayed ("untreated" and "untreated + shell"). In addition, oyster seed was planted on all treatments the following spring. Percentage of epibenthic shell cover, shrimp recruitment, oyster cultch retention, and oyster growth have been monitored at selected points in time over a period of 2 years.

On ghost shrimp ground at Nahcotta, the average amount of epibenthic shell cover on "untreated + shell" plots declined rapidly to 10% within 2 months after placement, whereas shell cover remained initially high on "treated + shell" plots but then declined gradually to 30% one year after placement (Figure 6.1). In contrast, on mud shrimp ground at Cedar River, mean shell cover was still 90% on both "treated + shell" and "untreated + shell" plots one year after placement (Figure 6.1). Although site characteristics may account for some of the differences in percentage of epibenthic shell cover between treatments, much of the variation could be attributed to differences in mobility, burrow stability, and general life history between the two species of shrimp.

At Nahcotta, the "treated + shell" plots had the lowest density of YOY ghost shrimp but the highest density of YOY mud shrimp one year after plot construction (Figure 6.2). Mean densities of oyster seed (cultch shell with spat) declined to nearly zero within 5 months on both "untreated + shell" and "untreated" plots (Figure 6.3), similar to trends in epibenthic shell cover on "untreated + shell" plots. Seed densities on "treated" and "treated + shell" plots were similar over the first summer; however a year later, seed densities appeared to somewhat higher on the "treated + shell" plots (Figure 6.3). Results from studies on oyster growth at Nahcotta are not yet available, nor are results from studies on shrimp recruitment, oyster seed retention, and oyster growth at Cedar River.

Although shell pavementing may prove to be a useful tool in combination with carbaryl to control ghost shrimp on some oyster beds, it is too soon to tell whether this technique would provide any benefit in areas inhabited by mud shrimp. Data from the USACE shell plot suggest, however, that epibenthic shell will not reduce recruitment of mud shrimp. Also, Smith (1996) found that oyster shell pavementing had no long-term negative impact on YOY mud shrimp recruitment in Yaquina Bay, Oregon. In addition to the effect of shell on benthic biota, other factors to consider with respect to shell pavementing are the cost of shell and the effect on harvest operations. It would take 19,530 bushels of shell to cover one hectare of mudflat at a thickness of 10 cm to 15 cm. Based on a cost of $1.13/bushel of shell, which is the average price paid by USACE for Dungeness crab mitigation (Lauren Cole-Warner, USACE, pers. comm.), it would cost approximately $22,000/ha or $9,000/acre for oyster shell. Additional costs would include the labor and boat time to deploy the shell. Although initial costs of shell pavementing may be expensive, once the ground is treated with carbaryl and shelled, it may continue to serve as a foundation for oyster culture years longer than pesticide treatment alone. Research studies are needed to evaluate the long-term effectiveness and associated costs of shell pavementing compared with other methods of shrimp control.

The transplanting and harvesting of oysters would likely be impacted by shell pavementing as well. If shell remained on the surface, it might interfere with dredging or hand-picking operations. The shell substrate might be dredged up along with oysters, or it might reduce the efficiency of the catch basket. In areas of the bay that receive natural seed set, epibenthic shell pavement could be transformed into an oyster reef (Brett Dumbauld, Washington Department of Fish and Wildlife, unpubl. data), which would be difficult to dredge and more difficult to hand-pick. On experimental plots of ghost shrimp at Nahcotta, however, most of the shell pavement on "treated + shell" plots eventually sank a few centimeters below the sediment surface, whereas oyster cultch generally remained on the surface. On a mud shrimp bed in Yaquina Bay, Oregon, Smith (1996) found only 5% of crushed oyster shell remained on the surface of plots one year after construction. Even though the shell sank, Smith (1996) determined that shelled plots were significantly more compact than were untreated mud plots. Thus, if shell pavement sinks, it might still provide a firm substrate for bottom-culture and yet not interfere greatly with oyster harvesting. Research is needed to determine how harvest operations would be impacted by both an epibenthic shell layer and a sub-surface shell layer to assess the feasibility of applying this technique to oyster culture.

Many of these ideas are still in a research-mode, and are not proven as effective means to control burrowing shrimp. Shell pavementing clearly changes the physical nature of the substrate, which undoubtably affects the composition of the benthic community that can live there. It remains to be determined whether this is valued or not, with respect to the abundance and distribution of living resources within the estuary. Thus, we can not recommend use of shell pavementing as a proven method to control burrowing shrimp at this time, although this method shows promise for use in the future.

6.3.7 Diking and Damming. Construction of earthen dikes, dams, or berms around oyster beds has been suggested as a possible method to exclude motile shrimp from colonizing shrimp-free oyster beds (L. Bennett, pers. obs.). Growers and biologists have reported lateral movement of shrimp over time from untreated tidal flats into oyster beds. Construction of barriers against lateral shrimp movement may slow reinfestation rates on the perimeters of oyster beds. Creation of dams and dikes was first used in Puget Sound for the culture of Olympic oysters earlier this century (Steele 1957). As occurred then, shrimp may simply burrow under or through dikes, dams, or berms. Tidal action and currents washing against earthen barriers would cause them to erode rapidly if they were not reinforced or constantly maintained. Finally, although lateral migration of shrimp has been observed to occur, it is generally thought that larval recruitment is the principal manner by which burrowing shrimp colonize tide flat sediments. Larval shrimp could simply swim (or float) over the barriers at high tide and settle on the oyster beds. Furthermore, eddies created behind dikes may actually enhance juvenile shrimp recruitment by concentrating pelagic larvae and depositing them on and near the dikes (Snelgrove and Butman 1994).

Although dikes and dams might have only temporary success stopping the lateral movement of burrowing shrimp, they might be useful for retaining water on beds at low tide, which could help reduce burrowing shrimp abundances in two ways. First, if dikes and dams retained very low salinity water (<5‰) as might occur during freshets or periods of high rainfall, burrowing shrimp might be osmotically shocked and die. Harrowing the substrate to help low salinity water penetrate into the sediment might facilitate this. Second, these pools might provide habitat for staghorn sculpin or sturgeon to forage for burrowing shrimp during periods when they would normally be restricted to deeper water. Methods would have to be developed to keep the fish on the oyster grounds at high tide (such as providing additional incentives, e.g., other habitat enhancements or mate-attracting pheromones) or to periodically reintroduce them to the tide flats. If these methods were conducted following recruitment of burrowing shrimp, the juvenile shrimp would be closer to the sediment surface and the potential for the control methods to work might be increased. Additionally, eelgrass beds would likely be enhanced within the artificial pools (B. Dumbauld, pers. comm.).

Many of these ideas are speculative and untried, and may have unexpected affects on other estuarine species living on, or using the tideflats. Thus, we can not recommend use of diking and daming as proven methods to control burrowing shrimp at this time.

6.3.8 Water Jets. Growers proposed using high-pressure jets of water to either winnow burrowing shrimp from the sediments, or to crush the shrimp with the force of the water jet. This method would be extremely disruptive, winnowing out fine-grained and organic matter components of the sediment and causing considerable resuspension of sediment into the water column. We were unable to find any studies to substantiate the efficacy of this method. It would seem as if an entire oyster bed would have to be subjected to this treatment to have assurance that the shrimp were killed. As with compaction, additional methods would be needed to collect or kill shrimp that were forced to the sediment surface, and this method could only be used on beds barren of oysters. Finally, the energy required to generate high-pressure water jets and the time required to treat large areas would probably make this method expensive. Given the considerable uncertainties and paucity of real information concerning this control method, we cannot objectively evaluate its efficacy, but there appear to be few compelling reasons to recommend further investigation of this approach.

6.3.9 Electro-shocking or Ultrasound. Passing an electric current or high frequency sound through the sediment of shrimp-infested oyster beds may have a negative effect on shrimp populations by directly affecting individual survival and reproduction. Little work has been done to explore these techniques. In preliminary trials using Electro-shocking in aquaria, both ghost shrimp and mud shrimp moved toward either the anode or cathode (this varied between species and properties of the electrical current), and sometimes toward the water surface if the shrimp were not residing deep within their burrows (B. Dumbauld, pers. comm.). However, the electrical fields did not cause many shrimp to leave their burrows, and the current used did not kill the shrimp. We know of no studies that have investigated the use of ultrasound to control burrowing shrimp, although such research has been proposed (B. Dumbauld, pers. comm.). Clearly, much research remains to be done to demonstrate whether either of these techniques will be effective at driving burrowing shrimp from their burrows or killing them. These ideas are speculative and largely untried, and may have unexpected affects on other estuarine species living on, or using the tideflats. Thus, we can not recommend use of Electro-shocking or ultrasound as proven methods to control burrowing shrimp at this time.

6.4 CULTURAL MEASURES TO MANAGE PEST DAMAGE

Cultural methods of managing the damage of a pest include changing aspects of the crop-growing practices to reduce the vulnerability of the crop to the pest, switching to other crops, or harvesting the pest for profit.

6.4.1 Reinforcement of Longline Culture Structures. Tice and Griffin (1993) recommended that longline culture operations could reduce the incidence of posts sinking or toppling and lines slipping off posts by increasing the length of the posts to 60 in. (from the current 40 in.), reducing the spacing between posts from 5 ft to 3 ft, and cutting tight notches at the top of posts to better hold the lines. The longer posts should be driven about 40 in. into the sediment (instead of approximately 20 in. that is currently used) to obtain better anchoring. The narrower spacing of posts reduces the weight on each post, thereby reducing some of the pressure that contributes to the sinking and toppling. Notches that more tightly grip the oyster lines would reduce the frequency of lines slipping from the posts if the posts were to lean as a result of shrimp burrowing. These steps would mitigate one of the impacts that burrowing shrimp have on longline cultures; however, they would increase the cost of materials and labor and would have no effect on the burial of oysters that fall off the longlines (about 50% of the crop).

6.4.2 Shrimp Harvest for Bait Industry. Currently, a cottage industry exists supplying burrowing shrimp to recreational fishermen, charter boats, and some commercial fishermen for use as bait. Individual harvesters use pumps or suction guns ("shrimp guns") to flush or pull burrowing shrimp out of the sediment. This method is thought to have little impact on both the shrimp populations and the oyster beds (L. Bennett, pers. obs.), because relatively few shrimp are harvested. The scale of individual operations is small because of the large effort required to harvest the shrimp and the relatively minor local market for the product. Larger-scale operations use suction dredge equipment, which, although capable of extracting large quantities of shrimp, leave the tidal flat unevenly pock-marked and oyster beds in a state less-than-optimum for oyster farming. The beds require about a year to recover from the damage (L. Bennett, pers. obs.). Harvesting shrimp may also be useful for controlling shrimp around the edges of oyster beds (i.e., border control), thereby slowing the rate of immigration of adult shrimp into oyster beds (B. Dumbauld, pers. comm.).

If large enough markets could be developed for sale of burrowing shrimp as bait to the commercial and charter fish industry, shrimp harvest in localized areas may effect a significant population reduction (L. Weitkamp, University of Washington, pers. comm.). Further investigations may determine whether the detrimental effects of suction dredges can be sufficiently mitigated or the use of less-damaging hand-held equipment be economically feasible or have a significant effect on shrimp populations. Oyster growers might also work with shrimp harvesters to develop new markets for burrowing shrimp, such as for Asian or other ethnic seafood trade.

These ideas are speculative and unproven as effective means to control burrowing shrimp, and may have unexpected affects on other estuarine species living on, or using the tideflats. Thus, we can not recommend use of burrowing shrimp harvesting as a proven method to control burrowing shrimp at this time.

6.4.3 Alternative Crops. In areas of high-density burrowing shrimp populations that are unsuitable for oyster culture, growers should consider culturing other species. Smith (1996) describes methods for growing Manila clams (*Venerupis japonica*) using shell pavement and predator-exclusion cages on mudflats infested with mud shrimp. This method did not succeed in ghost shrimp grounds because the cages sank too rapidly. This culture method did require occasional maintenance (approximately every 2 months) to ensure that the cages did not sink entirely below the sediment surface; as long as approximately 1 in. of the cage remained above the sediment, the clams grew quite well. On a half acre of ground, and relying on an initial capital investment of ~$15,500, Smith estimated a profit of $53,700 after five years; interested growers should refer to Smith (1996) to determine whether his economic assumptions would be applicable to their situation.

Following this line of reasoning, oyster growers should consider whether other marketable species of bivalves might exist or whether creating a market for species that are tolerant of burrowing shrimp is worth the risk. It is not clear what those species might be. And as suggested in the previous section, growers might investigate whether a market exists, or could be developed, for burrowing shrimp as a seafood item or component of a seafood product.

Many of these ideas are speculative and unproven as economically viable alternatives to oyster farming. Thus, we can not recommend use of Manila clam culture within burrowing shrimp beds as a proven alternative to oyster culture plus control of burrowing shrimp.

6.5 Evaluation of Control Methods by Oyster Growers and Other Experts

As part of our formal interviews, we asked oyster growers and knowledgeable non-growers to evaluate several shrimp management methods from two perspectives: effectiveness relative to carbaryl pesticide (growers only) and non-target impacts (growers and non-growers).

Table 6.2 summarizes the responses of five oyster growers (all who responded to this part of the interview) regarding the effectiveness of 10 shrimp control methods relative to carbaryl pesticide. The growers concluded that none of the control methods were likely to be more effective against burrowing shrimp than carbaryl. In contrast, we suspect that there are other pesticides that have equal or greater toxicity (or potency) to arthropods than carbaryl, with which growers have had little opportunity to evaluate (T. DeWitt and T. Wildman, pers. obs.); see Sections 6.1.3 and 6.1.4. Also, sediment barriers may be as effective as carbaryl at killing shrimp based on our experience using this method to defaunate experimental sediment plots (T. DeWitt, pers. obsv.); however, their efficacy on a large scale is difficult to judge. In our experience, shell pavement appears to be far more effective against ghost shrimp than against mud shrimp (see Section 6.3.6), but would probably be less effective than carbaryl.

The growers judged that most of the methods were technically feasible to apply on oyster beds, with the possible exception of the electroshock/ultrasound method, but none were scored as having achieved a high level of technical development. The methods with the greatest promise for successful technical development were enhancement of predators and shell paving; based on recent advances, we would add "other pesticides" to this list (Section 6.1.3). In our judgement, the technology for sediment compaction is available; as practiced in the past, sediment compaction was not effective, but with newer swamp tractors and methods of killing the shrimp as they emerge onto the sediment, improvements are possible.

The growers felt that most of the control methods would be more expensive to apply than carbaryl pesticide. On the other hand, the cost of harvesting burrowing shrimp as a saleable product in itself might generate enough revenue to outweigh the cost of carbaryl. Shrimp control methods on this list that show greatest promise for further technical development are other pesticides, predator enhancement, sediment barriers, sediment compaction, shell pavementing, and harrowing. They may not all be as effective as carbaryl at managing the damage caused by burrowing shrimp, none has been proven as an economically viable control practice for commercial oyster beds, and each may have unexpected adverse environmental impacts; however, these six methods still show the greatest promise of utility for the future.

Table 6.3 and Table 6.4 summarize the evaluation by five oyster growers and six non-grower experts, respectively, of the long-term, non-target effects of 11 shrimp control methods (i.e., the ten used in the previous evaluation plus carbaryl pesticide). People we interviewed were asked to score the long-term impacts of each method on environmental and human resources, with scores from 1 for highly detrimental to 10 for highly beneficial; a value of 5.5 would, therefore, be equated with "no long-term effect". Several patterns emerge from these tables.

- First, both growers and non-growers felt that most shrimp control methods would have either a beneficial effect or no-effect on most environmental and human resources. This response is demonstrated by the comparatively few dark-shaded cells in both tables relative to unshaded or lightly shaded cells.
- Second, there were no major conflicts between evaluations made by growers and those made by non-growers. That is, in no case did growers rank a method

as beneficial to a specific resource and non-growers rank it as detrimental to the same resource.

- Third, growers, as a group, tended to be more environmentally conservative about non-target impacts of control methods than non-growers, as a group. This is reflected in the greater number of shaded cells in the grower's evaluation (24; Table 6.3) than in the non-grower's evaluation (15; Table 6.4).

- Fourth, pesticides and predator enhancement were viewed as having beneficial effects on several environmental and human resources. Growers viewed more resource categories as benefitting from these two control methods than did non-growers. In particular, growers viewed carbaryl as beneficial to all categories of environmental resources.

- Fifth, environmental resources were more likely to be detrimentally affected than human resources. Water quality, fish, eelgrass, and benthic invertebrates were recognized as the most vulnerable environmental resources, and health was identified as the most vulnerable human resource.

- Sixth, non-growers and growers in combination felt that other pesticides, sediment barriers, substrate compaction, clay injection, water jets, and Electro-shocking- ultrasound could adversely affect three or more categories of environmental and human resources. Of these, sediment barriers, substrate compaction, and clay injection were viewed as impacting the greatest range of resource categories.

- Finally, only three shrimp control methods were viewed as being without substantial, long-term detrimental impact: carbaryl pesticide, predator enhancement, and shrimp harvest. Shell pavement was viewed as being detrimental to eelgrass, but was otherwise scored as having no effect on resources.

6.6 INTEGRATION OF CONTROL MEASURES

Relatively little work has been conducted formally to investigate the benefits of integrating different control measures to control burrowing shrimp on oyster beds. However, as terrestrial growers have learned, using pest control measures that compliment one another and taking advantage of the ecology of the pest and its natural enemies can reduce the damage caused by the pest without resorting to drastic tactics in the arsenal. In this section, we speculate on possible opportunities for integrating control methods and suggest some promising possibilities that could be investigated. However, it must be recognized that none of these integrated control methods have been tried on a commercial-scale oyster bed (and in several cases, they are completely untried), that their effectiveness at controlling burrowing shrimp is not known, and that they might have unexpected adverse effects on oyster yields or estuarine organisms. Thus, we are not recommending that any of these integrated methods be put into practice, but that they be considered as suggestions for future investigation.

Shell Pavement and Predation. Shell pavement can hinder the burrowing of ghost shrimp and attracts YOY Dungeness crabs that will prey on recruiting ghost shrimp. This was discussed in Section 6.3.6.

Chemical Control and Predator Habitat Enhancement. Eelgrass beds (which serve as habitat for burrowing shrimp predators) may be vulnerable to disruption by ghost shrimp, particularly from the burrowing activity of shrimp at the margin of the bed. Application of pesticide (carbaryl) to kill ghost shrimp can result in growth of eelgrass on substrates formerly devoid of vegetation (L. Bennett, pers. obs.; B. Dumbauld, pers. comm.). Initial application of pesticide to promote the development of eelgrass, or the targeted use of pesticide to control ghost shrimp around the perimeter of eelgrass meadows (probably by hand spraying) could serve to enhance eelgrass bed size, which in turn might enhance the local abundance of burrowing shrimp predators.

Chemical Control and Shell Pavement. Shell pavement applied over existing ghost shrimp beds will rapidly sink into the sediment, which is softened as a result of bioturbation by the shrimp. Application of a pesticide (carbaryl or suitable alternative) to eradicate the shrimp prior to applying the shell will greatly increase the lifespan of the shell layer (B. Dumbauld and K. Feldman, pers. comm.).

Chemical Control and Physical Barriers. As with shell pavement, application of a pesticide to remove burrowing shrimp prior to laying down a physical barrier (particularly a semi-permeable barrier) would increase the lifespan of the barrier as well as simplify its installation.

Timing of Control Actions (Chemical, Biological, or Physical) with Recruitment of Shrimp. As described in Section 6.3.3, burrowing shrimp may be most vulnerable to physical disturbance or predation immediately following settlement of new YOY recruits, which is spring for mud shrimp and fall for ghost shrimp (see Section 4.5). Recruitment may be the dominant process controlling population growth of burrowing shrimp. Targeting control practices to kill YOY shrimp may be more effective than targeting adults.

Sediment Compaction (or Harrowing) and Shrimp Harvesting or Predation. Disruption of the substrate by sediment compaction or harrowing can cause adult burrowing shrimp to emerge onto the sediment surface. Mechanical harvesting of the shrimp (using nets) or enhancement of predators might increase shrimp mortality. Timing this activity to follow recruitment of shrimp would increase the duration of the control measure. Methods of enhancing predation could include release of predators onto beds following substrate disruption (YOY Dungeness crabs or staghorn sculpin probably offer the best chances of success), attraction of predators to the site (this might be especially effective for birds), or conducting the operation in close proximity to predators' habitat (such as eelgrass beds). These methods might be best applied to barren oyster ground (i.e., before oysters are placed on the substrate) because of the damage the physical control methods would cause to the oysters.

Predator Habitat Enhancement and Cultural Practices. Promoting the growth of eelgrass meadows on or adjacent to bottom culture or longline oyster beds might enhance the local abundance of burrowing shrimp predators (especially fish and crabs). Methods might be developed to minimize eelgrass interferences with oyster culturing. For example, it may be possible to "grow" strips of eelgrass meadows across oyster beds and to culture oysters between the meadows. This is analogous to strip cropping or companion planting in terrestrial agriculture. Studies would have to be conducted to determine if the presence of eelgrass beds reduces burrowing shrimp abundance (particularly ghost shrimp), and if so, what dimensions of oyster ground and eelgrass meadows maximizes the reduction of shrimp populations. It should be recognized that tidal currents moving between eelgrass beds can erode sediments and thereby create sloughs on the tideflats that are detrimental to bottom culture of oysters (L.

Bennett, pers. obs.); thus, the spacing of eelgrass beds would need to set so that erosion is minimized.

Diking and Damming and Predator Enhancement. As described above, foraging by finfish and crab predators is limited to when the tide flats are inundated with water. Creation of artificial tide ponds by diking and damming intertidal oyster beds, thereby creating habitat that might allow the fish and crabs more opportunity to prey on burrowing shrimp. The hydrostatic pressure of water in the ponds would likely restrict the depth of such pools to a few inches, thus limiting this system to small predators, such as staghorn sculpin and Dungeness crabs. Additional actions might be needed to attract sufficient numbers of predators to the ponds, such as provision of favored habitat elements or baits with food or reproductive chemical attractants. The effectiveness of these methods might be further enhanced if they were used during periods of burrowing shrimp recruitment.

Diking and Damming and Low Salinity. Since neither species of burrowing shrimp can tolerate low-salinity (<5‰), tidal ponds created by diking and damming might be used to retain low-salinity or fresh water on the tide flat during low tide, thereby prolonging the period of time that the shrimp are exposed to natural lethal conditions. Furthermore, the hydrostatic head of the water in the ponds might help force low-salinity water into the burrows of the shrimp and increase their exposure to the lethal conditions. This method might be more readily used against ghost shrimp than mud shrimp, because ghost shrimp are less tolerant of low salinity. Unless growers had the means to pump large volumes of freshwater into these pools, use of these methods would probably be limited to periods of flooding and heavy rainfall, which might not be especially convenient or safe times for oyster growers to be on the water.

Harrowing and Low Salinity. Similar to the previous integrated method, harrowing might help mix low-salinity water into the sediment, bringing the shrimp into greater contact with natural lethal conditions. Obviously, this method would require that the salinity of the water overlying the tide flat be low (<5‰), such as during freshets and floods. One major uncertainty is whether harrowing could significantly alter the porewater salinity. This method might be more effective against YOY shrimp than adult shrimp, because their burrows would not extend far below the sediment surface; disruption of the sediment by the harrow would be greatest in the upper few inches of the tide flat. As with diking and damming, this method might be more effective against ghost shrimp than mud shrimp because of a lower tolerance to low-salinity conditions. Because harrowing can cause oysters to sink into the sediment (L. Bennett, pers. obs.), this method might best be applied to oyster beds either just prior to harvesting (or transplanting in the case of immature oysters) or on barren beds (prior to setting out oysters).

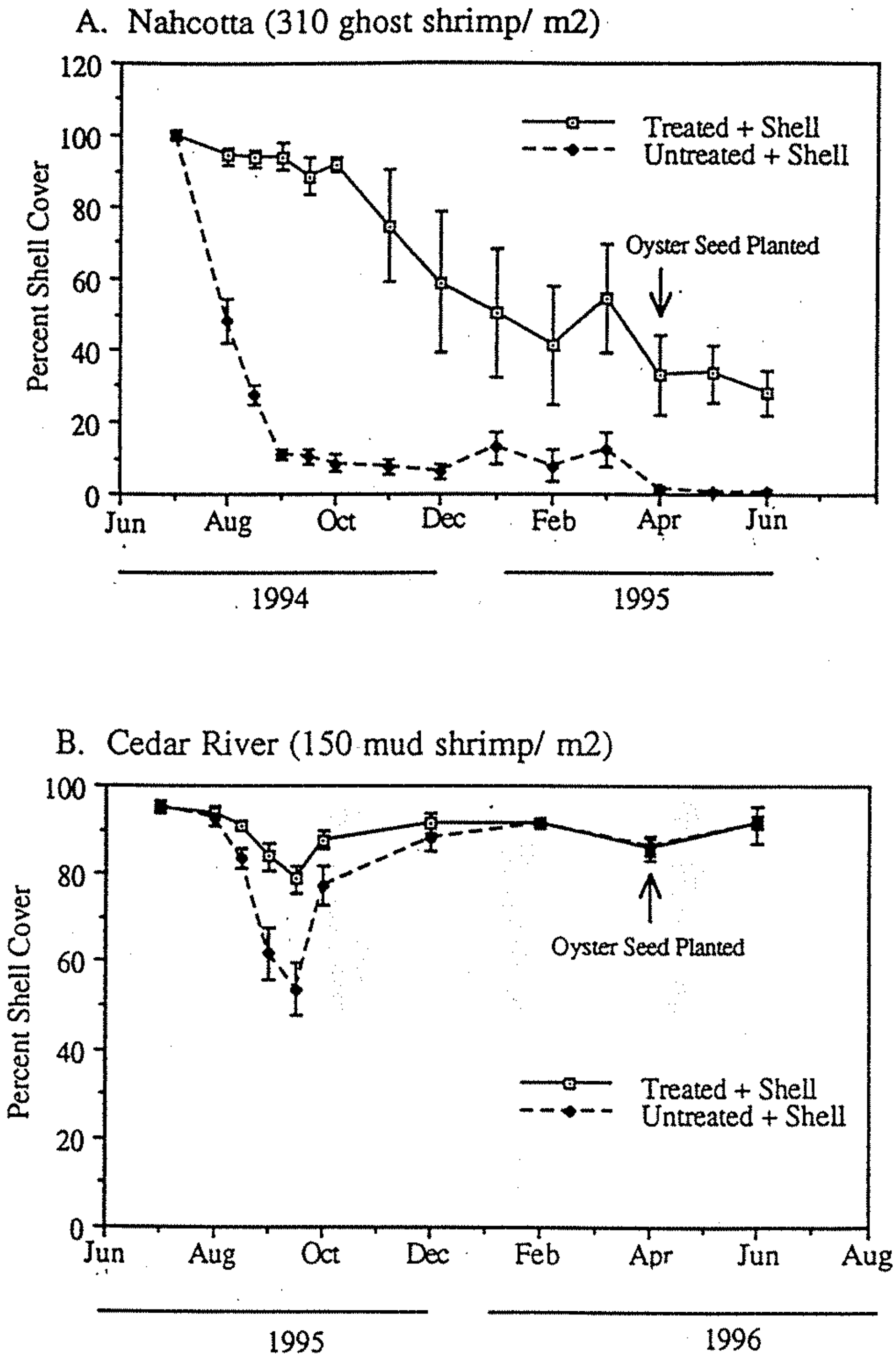


Figure 6.1 Comparison of mean percentage of shell cover (± 1 SE) on "treated + shell" and "untreated + shell" plots on (A) ghost-shrimp infested ground at Nahcotta and (B) mud-shrimp infested ground at Cedar River, Willapa Bay. Values at top of panels are mean shrimp density at start of experiments (K. Feldman, B. Dumbauld, and D. Armstrong, unpubl. data).

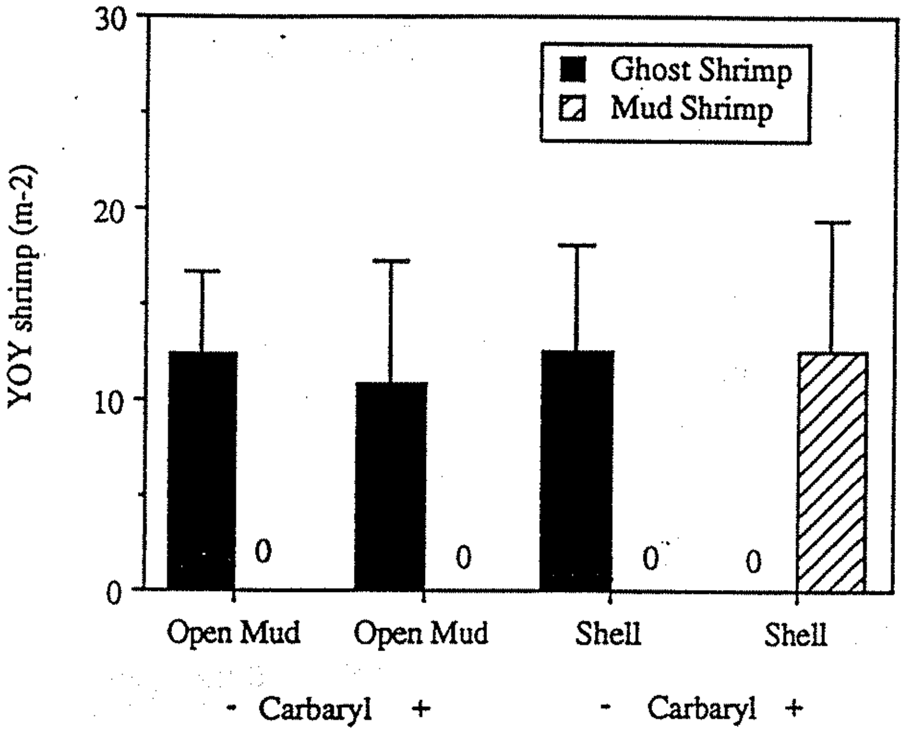


Figure 6.2 Mean densities m^{-2} (± 1 SE) of young-of-the-year (YOY) ghost shrimp and YOY mud shrimp on experimental plots at Nahcotta, Willapa Bay, in June 1995. Note that ghost shrimp were present in all treatments except "treated + shell" plots, whereas mud shrimp were absent in all treatments except "treated + shell" (K. Feldman, B. Dumbauld, and D. Armstrong, unpubl. data).

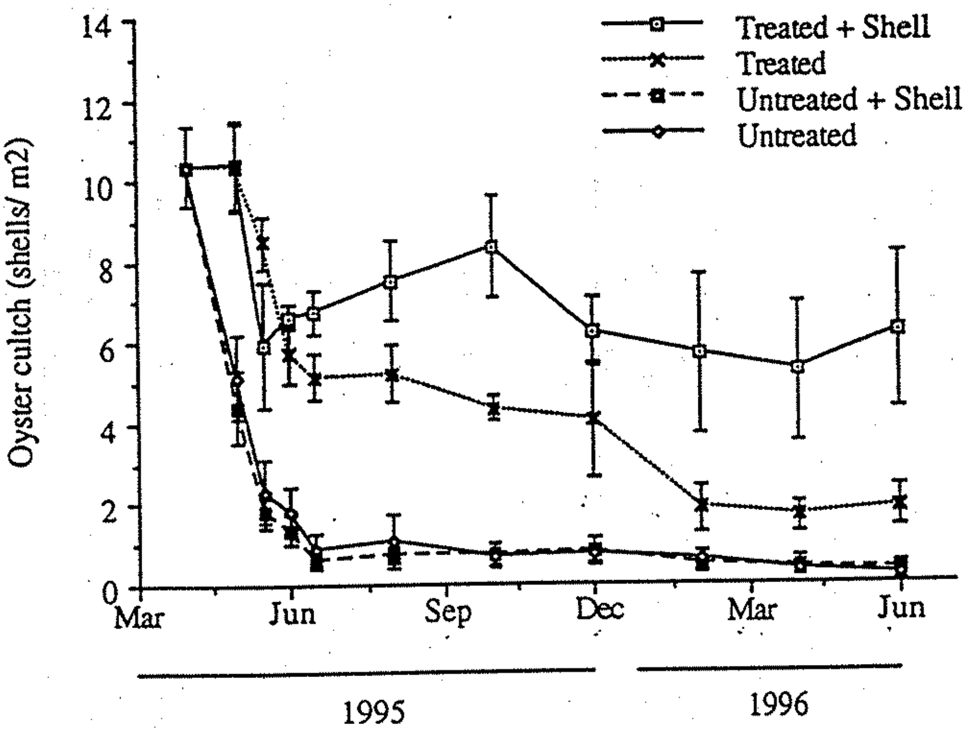


Figure 6.3 Mean densities m^{-2} (± 1 SE) of cultch (shells covered with oyster spat) on experimental plots on ghost shrimp ground at Nahcotta, Willapa Bay (K. Feldman, B. Dumbauld, and D. Armstrong, unpubl. data).

Table 6.1. Summary of Current and Previously Proposed Methods of Controlling Burrowing Shrimp Populations on Oyster Grounds

Method	Description	Mode of Action	Comments
Chemical Control			
Carbaryl Pesticide	General-purpose pesticide sprayed by helicopter or by hand onto tide flat at low tide	Arthropod neurotoxin	Currently, most widely used method
Other Pesticides	Pesticides with low non-target toxicity, applied to tide flat surface by hand or helicopter	Various toxicological mechanisms: hormone mimics, developmental regulators, neurotoxins	None in use, but several candidates possible. Considerable regulatory and public scrutiny likely.
Biological Control			
Predator Enhancement	Increase population size and diversity of natural shrimp predators (finfish) within the estuary	Burrowing shrimp consumed	Research underway with Dungeness crabs. Salmonid restoration efforts might help. Sturgeon populations reported to be increasing.
Physical Control			
Sediment barriers	Cover shrimp-infested beds with sheets of plastic or mesh	Kills by smothering (anoxia) and prevents burrowing	Currents and storms move or destroy sheets; produces plastic debris. Limited small-scale success.
Substrate Compaction	Pulling weighted rollers, wheels, or sleds across tide flat that compact sediment and collapse shrimp burrows	Crushes or smothers shrimp, or forces them to sediment surface where they are harvested	Effective but hard on machinery and labor intensive. Cost- effectiveness not evaluated. Used on small scale in past.
Dredge-Harvesting of Oysters	Mechanical harvesting of bottom-cultured oysters disturbs juvenile burrowing shrimp that have shallow burrows	Crushes or winnows YOY burrowing shrimp from sediments	May have some efficacy for YOY ghost shrimp, but only limited evaluations have been conducted.

Table 6.1. Summary of Current and Previously Proposed Methods of Controlling Burrowing Shrimp Populations on Oyster Grounds

Method	Description	Mode of Action	Comments
Harrowing	Boat-towed harrows disrupt top few inches of sediment	Crushes or lacerates shrimp, or forces them to sediment surface where they are harvested	Tried repeatedly with mixed success. Cost-effectiveness not assessed.
Clay Injection	Inject slurry of bentonite clay into shrimp burrows to smother shrimp or be irritant that causes shrimp to emerge onto the sediment surface	Smothering agent or irritant that forces them to sediment surface where they are harvested	Largely ineffective because shrimp clear clay from their burrows before clay can set up. Not in use.
Shell or Gravel Paving	Cover surface of tide flat with thick layer of shell or gravel that shrimp cannot burrow through and attracts predators of juvenile shrimp	Inhibit burrowing behavior; attracts crab predators	May be effective against ghost shrimp, unclear effect on mud shrimp. May impact non-target organisms. Cost-effectiveness not assessed. Research underway.
Diking and Damming	Create berms to slow lateral movement of shrimp or shallow ponds to hold predators on oyster beds at low tide	Indirect method: slows infestation rate or provides habitat for predators	No studies have evaluated these methods, but they may have potential for integration with other tactics, especially predator enhancement
Water Jets	Direct stream of water into sediment to winnow out shrimp or kill them by crushing	Pump shrimp to surface, then harvest or kill by mechanical means, or directly crushes shrimp	May not be practical on large scale. Cost-effectiveness not assessed.
Electro-shocking or Ultrasound	Electromagnetic or acoustic field causes shrimp to leave burrows and emerge onto tide flat surface	Force shrimp to surface, then harvest or kill by mechanical means	Efficacy uncertain. May not be practical on large scale. Cost-effectiveness not assessed.

Table 6.1. Summary of Current and Previously Proposed Methods of Controlling Burrowing Shrimp Populations on Oyster Grounds

Method	Description	Mode of Action	Comments
Cultural Methods			
Reinforce Posts for Longline Culture	Lengthen posts and sink them deeper in sediment so that burrowing shrimp cannot cause posts to sink or topple	Reduce damage to cultures by stabilizing oyster-support structures that can be undermined by shrimp	Post sinking and toppling is only one of the ways in which shrimp impact longline culture. Others include hindering access to beds and burial of portion of crop (50%) that falls from lines to sediment surface (i.e., becomes bottom culture).
Alternative Crop	Replace oysters with another cash crop such as Manila clams	Farm an alternative species that is more tolerant of burrowing shrimp than oysters	Manila clams might work in rack and cage culture within mud shrimp habitat, but are vulnerable to ghost shrimp damage.
Harvest Burrowing Shrimp	Pump or flush shrimp from their burrows and sell them as a product	Physical extraction of shrimp from sediment	Shrimp currently sold only as fish bait; markets limited and local. Potential as food product for ethnic seafood or medicinal market has not been pursued.

Table 6.2. Evaluation by Oyster Growers of the Effectiveness of Burrowing Shrimp Control Methods Relative to Carbaryl Pesticide

Control Method	Effect on Shrimp	Technical Feasibility	Cost to Apply	Personal Experience
Other Pesticides	u	1	=	0
Predator Enhancement	-	2	u	0
Sediment Barriers	-	1	+	1
Sediment Compaction	-	1	+	2
Clay Injection	-	1	+	0
Shell Pavement	-	2	+	2
Harrowing	-	1	+	2
Water Jets	u	1	+	1
Electroshock	u	u	+	0
Shrimp Harvest	u	1	+	1

Key				
	+ more effective than carbaryl	0 - unlikely to develop	+ more $ than carbaryl	0 - none
	- less effective than carbaryl	1 - technically possible, success uncertain	- less $ than carbaryl	1 - tried on small scale
	= as effective as carbaryl	2 - technology exists, success possible	= same $ as carbaryl	2 - used on some beds
	U uncertain	3 - technology proven	U uncertain	3 - used regularly
		U uncertain		

Table 6.3. Evaluation of Long-term Non-target Effects of Burrowing Shrimp Control Practices by Oyster Growers (Average, Range). Ranking was on scale of 1(high detrimental impact) to 10 (high beneficial impact); 5.5 was no long-term impact. Dark shaded cells had average values < 4.0 (detrimental); lightly shaded cells had average values ≥7.0 (beneficial); unshaded cells had average values between 4.1 and 6.9 (no-effect).

Control Method	Water Quality and Debris	Mammals	Birds	Fish	Benthic Inverte-brates	Eelgrass	Short-term Human Health Effects	Long-term Human Health Effects	Recreation Revenues, Jobs, or Income	Fishery Revenues, Jobs, or Income	Overall Economic Effects	Average
Carbaryl Pesticide	7.2 (5 - 10)	8.0 (5 - 10)	8.8 (7 - 10)	7.6 (5 - 10)	8.4 (5 - 10)	8.4 (5 - 10)	6.2 (2 - 10)	6.8 (5 - 10)	8.8 (5 - 10)	9.6 (9 - 10)	9.8 (9 - 10)	8.1 (6.5 - 10)
Other Pesticides	5.0 (2 - 8)	6.0 (2 - 8)	6.3 (1 - 10)	4.7 (1 - 8)	5.3 (1 - 10)	7.7 (5 - 10)	3.0 (2 - 5)	3.5 (2 - 5)	7.3 (2 - 10)	7.3 (2 - 10)	7.3 (2 - 10)	5.9 (2.5 - 8.1)
Enhance Predators	8 (9 - 10)	5.3 (1 - 10)	7.0 (5 - 10)	8 (6 - 10)	5.7 (2 - 10)	6.7 (5 - 10)	6.7 (5 - 10)	6.7 (5 - 10)	8.3 (5 - 10)	8.3 (7 - 10)	9 (7 - 10)	7.1 (5.5 - 10)
Sediment Barriers	1.7 (1 - 3)	2.3 (1 - 5)	2.3 (1 - 5)	1.7 (1 - 3)	2.0 (1 - 3)	1.0 (1 - 1)	6.3 (1 - 9)	6.3 (5 - 9)	5.0 (2 - 8)	5.3 (2 - 9)	4.3 (2 - 6)	3.5 (2.2 - 5.5)
Substrate Compaction	2.7 (1 - 5)	5.0 (2 - 5)	4.3 (1 - 9)	3.0 (1 - 5)	3.7 (1 - 8)	4.0 (1 - 6)	6.0 (5 - 8)	6.0 (5 - 8)	5.0 (2 - 8)	5.3 (2 - 9)	5.0 (2 - 8)	4.5 (2.1 - 7.1)
Inject Clay	3.3 (1 - 5)	5.0 (4 - 5)	3.7 (1 - 5)	3.7 (1 - 5)	4.3 (1 - 8)	3.7 (1 - 5)	6.0 (5 - 8)	6.0 (5 - 8)	6.5 (5 - 8)	6.5 (5 - 8)	6.5 (5 - 8)	4.5 (2.1 - 6.6)
Shell or Gravel	5.3 (5 - 7)	5.0 (4 - 5)	6.0 (5 - 8)	6.0 (5 - 8)	6.7 (5 - 8)	3.0 (2 - 4)	5.7 (4 - 7)	5.7 (5 - 7)	7.0 (5 - 9)	7 (5 - 9)	7.0 (5 - 9)	5.8 (4.8 - 6.5)
Harrowing	5.3 (5 - 6)	4.3 (1 - 7)	4.3 (1 - 7)	4.3 (1 - 7)	5.0 (1 - 7)	4.3 (1 - 7)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1.4 - 7.4)
Water Jets	3.0 (1 - 6)	4.3 (1 - 7)	4.3 (1 - 7)	3.7 (1 - 7)	4.0 (1 - 7)	3.0 (1 - 5)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.2 (1 - 7.2)
Electroshock or Ultrasound	6.0 (5 - 8)	4.3 (1 - 7)	4.3 (1 - 7)	3.0 (1 - 7)	3.7 (1 - 7)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.7 (1 - 8)	4.5 (1.4 - 7.6)
Shrimp Harvest	5.0 (5 - 6)	4.7 (2 - 7)	5.0 (3 - 7)	4.7 (3 - 7)	4.3 (2 - 7)	4.7 (1 - 7)	5.7 (5 - 7)	6.0 (5 - 8)	6.3 (5 - 8)	6.3 (5 - 8)	6.3 (5 - 8)	5.4 (3.7 - 7.2)

Table 6.4. Evaluation of Long-term Non-target Effects of Burrowing Shrimp Control Practices by Expert Non-growers (Average, Range). Ranking was on scale of 1(high detrimental impact) to 10 (high beneficial impact); 5.5 was no long-term impact. Dark shaded cells had average values < 4.0 (detrimental); lightly shaded cells had average values ≥7.0 (beneficial); unshaded cells had average values between 4.1 and 6.9 (no-effect).

Control Method	Water Quality and Debris	Mammals	Birds	Fish	Benthic Inverte-brates	Eelgrass	Short-term Human Health Effects	Long-term Human Health Effects	Recreation Revenues, Jobs, or Income	Fishery Revenues, Jobs, or Income	Overall Economic Effects	Average
Carbaryl Pesticide	5.7 (3 - 9)	6.0 (5 - 10)	6.0 (4 - 10)	5.5 (2 - 10)	4.7 (1 - 10)	6.3 (4 - 10)	4.2 (3 - 5)	6.3 (5 - 10)	6.8 (5 - 10)	7.0 (3 - 10)	7.8 (5 - 10)	**6.1 (3.7 - 9.9)**
Other Pesticides	3.7 (2 - 5)	5.6 (3 - 10)	5.2 (2 - 10)	5.4 (2 - 10)	4.8 (1 - 10)	6.4 (3 - 10)	4.3 (3 - 5)	5.3 (4 - 7)	6.4 (5 - 10)	7.6 (5 - 10)	7.1 (6 - 10)	**5.9 (3.5 - 10)**
Enhance Predators	6.8 (5 - 9)	5.8 (5 - 8.5)	6.3 (5 - 10)	6.5 (5 - 10)	6.5 (4 - 10)	6.8 (5 - 10)	5.8 (5 - 8)	6.0 (5 - 8)	7.2 (5 - 10)	7.0 (5 - 9)	7.3 (5 - 10)	**6.6 (5 - 8.7)**
Sediment Barriers	2.9 (2 - 4)	4.3 (4 - 5)	4.2 (3 - 7)	4.5 (2 - 7)	3.0 (1 - 6)	2.5 (1 - 4)	5.0 (5 - 5)	5.0 (5 - 5)	5.6 (3 - 8.5)	5.6 (3 - 8.5)	6.0 (3 - 10)	**4.4 (3.3 - 5.9)**
Substrate Compaction	3.5 (2 - 5)	5.3 (5 - 7)	5.3 (3 - 7)	4.7 (3 - 7)	2.2 (1 - 3)	2.8 (1 - 5)	5.0 (5 - 5)	5.0 (5 - 5)	6.0 (3 - 10)	6.0 (3 - 10)	6.0 (3 - 10)	**4.6 (3.6 - 6.5)**
Inject Clay	3.8 (1 - 7)	5.3 (5 - 7)	5.3 (4 - 7)	4.8 (4 - 7)	3.5 (2 - 5)	4.2 (3 - 7)	5.0 (5 - 5)	5.0 (5 - 5)	5.8 (3 - 10)	6.0 (3 - 10)	6.0 (3 - 10)	**4.9 (3.7 - 7.2)**
Shell or Gravel	5.5 (4 - 10)	5.2 (5 - 6)	5.7 (4 - 10)	5.5 (4 - 10)	4.2 (2 - 10)	4.3 (2 - 10)	5.8 (5 - 10)	5.8 (5 - 10)	6.2 (5 - 10)	6.5 (5 - 10)	6.5 (5 - 10)	**5.5 (4.4 - 9.6)**
Harrowing	4.5 (2 - 10)	5.7 (4 - 10)	5.5 (3 - 10)	5.2 (4 - 10)	4.0 (2 - 10)	3.8 (2 - 10)	5.8 (5 - 10)	5.8 (5 - 10)	5.8 (4 - 10)	6.2 (4 - 10)	6.0 (4 - 10)	**5.3 (3.9 - 10)**
Water Jets	4.2 (2 - 10)	5.5 (3 - 10)	5.5 (3 - 10)	5.3 (3 - 10)	3.8 (1 - 10)	4.0 (1 - 10)	5.8 (5 - 10)	5.8 (5 - 10)	5.8 (3 - 10)	6.0 (3 - 10)	6.0 (3 - 10)	**5.2 (3.1 - 10)**
Electroshock or Ultrasound	5.7 (3 - 10)	5.3 (3 - 10)	5.5 (3 - 10)	4.3 (2 - 10)	4.2 (2 - 10)	5.5 (3 - 10)	4.2 (1 - 5)	5.7 (4 - 10)	5.8 (4 - 10)	6.2 (4 - 10)	6.5 (4 - 10)	**5.3 (3.5 - 9.2)**
Shrimp Harvest	5.7 (3 - 10)	5.2 (5 - 6)	6.0 (5 - 10)	5.7 (4 - 10)	4.5 (1 - 10)	4.7 (2 - 10)	6.0 (5 - 10)	6.0 (5 - 10)	6.2 (5 - 10)	6.3 (5 - 10)	6.8 (5 - 10)	**5.7 (4 - 9.5)**

7.0 CRITERIA FOR INITIATING CONTROL PRACTICES

IPM requires that scientifically based, objective criteria be used as the basis for deciding when and where control tactics are to be deployed. In this chapter, we review and evaluate existing criteria used to decide which oyster beds qualify for carbaryl pesticide treatment, theoretical models used in IPM to develop decision criteria and thresholds, and the applicability of those models to the control of burrowing shrimp on oyster beds. Critical thresholds of pest densities are typically generated from these models, from which sampling plans are developed to determine whether the abundance of the pest has reached or exceeded the threshold. At the end of this chapter, we demonstrate how a sampling plan should be developed in order to implement the decision criteria.

7.1 REVIEW OF EXISTING CRITERIA AND THRESHOLDS

Carbaryl pesticide has been the dominant method used to control burrowing shrimp on oyster beds since the 1960s and is the only control method for which treatment criteria or thresholds have been formally developed. A threshold density of 10 burrows per square meter (b/m^2) has been used since 1978 (actually, 10 b/y^2 from 1978 to 1985) to determine whether there was sufficient need for carbaryl treatment (WDF/WDOE 1985). Beds with densities of 5 b/m^2 to 10 b/m^2 were evaluated on a case-by-case basis by regulatory agencies (WDFW) until 1985. These thresholds were established based on a determination by WDFW staff that some decision criteria were necessary and that growers typically did not apply for carbaryl permits when beds had an average density of fewer than 5 b/m^2 (D. Tufts and B. Dumbauld, pers. comm.).

As was discussed in Chapter 4, oyster growers conduct burrow-count census surveys in March and April so that these data can be included in applications for permits to treat beds with carbaryl. The seasonal timing of the surveys is dictated by the WDOE (and previously, WDFW), which requires that the applications be submitted no later than May. The May deadline is required so that the agency has sufficient time to review the applications and issue permits prior to the mid-summer low tides when carbaryl spraying must be scheduled. However, there is compelling evidence that burrow counts made in early spring bear no relationship to the true number of burrowing shrimp that constructed the burrows (Fig. 4.8 top;

see discussion in Section 4.6). Burrow counts taken from May to October provide more accurate predictions of burrowing shrimp population densities. However, the burrow/shrimp relationship can also vary with location (Fig. 4.8 bottom). Thus, the accuracy of a treatment threshold of 10 b/m^2 based on pre-May burrow counts is highly suspect. Although state fisheries biologists have known about this for some time (Tufts and Cooke 1983), it is likely that the current threshold has been retained because of the institutional constraint that growers must complete burrow-count census surveys by April to meet the May filing deadline. Thus, institutional and regulatory constraints force the growers and regulatory biologists to rely on inaccurate information to make decisions on which oyster beds merit treatment by carbaryl.

We could not find any data relating the density of burrowing shrimp (or their burrows) and the damage caused to oysters. Dumbauld (1994) conducted several studies examining the relationships between burrowing shrimp density, carbaryl treatment, and the survival of oysters (primarily seed) at different spatial scales and in different locations within Willapa Bay. He found rapid loss of seed in ghost shrimp beds associated with high shrimp densities, but could not establish a density-damage relationship attributable to the ghost shrimp occupying his experimental plots (i.e., sediment resuspension by shrimp on tide flats surrounding the plots interfered with the experimental treatments on his plots). Dumbauld also found relatively lower rates of seed burial associated with high densities of mud shrimp, but he was likewise unable to measure an impact that was unequivocally caused by the mud shrimp on the experimental plots (see discussion in Section 4.7.1). Armstrong et al. (1992) reported that oyster shell sank or was buried when ghost shrimp densities exceeded 40/m^2, but did not investigate lower densities other than 0/m^2; thus, their data suggests a threshold would be between 0/m^2 and 40/m^2. There is no doubt that ghost and mud shrimp have a deleterious effect on seed and adult oysters, but insufficient research has been conducted to objectively quantify the relationship between shrimp density and oyster loss for either species.

Furthermore, the current criteria and thresholds do not distinguish between ghost shrimp and mud shrimp, even though growers and biologists know that the two species have different impacts on oysters. As was previously discussed, ghost shrimp and mud shrimp have different life histories, habitat requirements, feeding behaviors, and effects on other benthic organisms (Chapter 4). Additionally, mud shrimp typically construct fewer burrows/shrimp than do ghost shrimp (Fig. 4.9), further obscuring the predictive accuracy of the burrow-count census data.

Thus, the current threshold for carbaryl treatment does not distinguish between pest species that have different capacities to harm oyster crops.

Clearly, there are serious flaws in the current criteria and thresholds for deciding when and where to apply carbaryl to control burrowing shrimp. Institutional constraints and lack of knowledge about cause-and-effect relationships (i.e., shrimp density and damage to oyster yield) underlie the problems with the 10 b/m^2 threshold. Continued reliance on the existing burrow count method may lead to failure to treat beds that need shrimp control (causing economic impacts) or the treatment of beds that are not in immediate need to treatment (causing unnecessary short-term environmental impacts).

Obvious ways of remedying this situation involve directed studies to determine the relationship between shrimp density and damage to oysters, improvements to the methods to census burrowing shrimp, and development of models to predict future (1-year hence) densities of burrowing shrimp. These studies could be conducted over a 2-year period. Additionally, regulatory agencies should change their permit review process to reduce the turnaround time from application to decision to enable a more reliable shrimp density data (i.e., collected in May or June) to be used to assist the decision-making process.

7.2 Overview of Decision-Criteria Models in Terrestrial IPM

Integrated pest management (IPM) programs can provide individual pesticide users with techniques proven to reduce pesticide use. Four general goals of IPM are to 1) reduce pest status; 2) ensure producer profits; 3) attain environmental compatibility; and 4) produce sustainable solutions to pest problems. Traditionally, IPM uses economic injury level (EIL) and economic threshold (ET) models to establish objective criteria that are used to determine when and where control tactics are deployed. The EIL and ET concepts emerged as an encouragement for the more rational use of pesticides (Stern et al. 1959), and to date, have been used only for chemical control tactics (L. Higley, Nebraska State University, pers. comm.).

The EIL indicates where management of a pest is economically justified. Thus, the EIL is the density of pests that causes economic damage to the crop (per unit of production) that is equal to the economic cost to manage the pest to that density or lower (Fig. 7.1). The term "economic" in EIL implies the original intent of enabling the grower to save money by eliminating unnecessary pesticide applications. Reduction of pesticide usage is a coincidental, albeit highly important and desirable consequence of using EILs (Flint and Van den Bosch 1981). Stern et al. (1959) defined ET as the population density at which control measures should be implemented to prevent an increasing pest population from reaching the EIL. The ET differs from the EIL in that it uses information about the population growth rate of the pest to determine when control efforts should be initiated to prevent the pest population from reaching the EIL density. Thus, the ET is the actual "trigger" for the initiation of control methods.

The EIL and ET concepts were originally designed as decision tools to be used within the context of the IPM approach to controlling insect pests of agricultural crops. Stern et al. (1959) envisioned these ideas as critical parts of the concept of integrated control, a new approach at the time, recommended as a replacement for the overly simplistic plan of "identify" and "spray" (Pedigo 1989). The utility of the EIL and ET as pest management practices assumes that control actions can be taken sufficiently quickly when the pest density reaches the ET that the grower can actually prevent the pest density from reaching the EIL, thereby preventing loss to the crop.

7.2.1 Economic Damage and the Damage Boundary. Economic damage was originally defined as the amount of injury that will justify the cost of artificial control measures. Pedigo (1989) suggests distinguishing between injury and damage. He defines injury as the "effect of pest activities on host physiology that is usually deleterious. Damage is a measurable loss of host utility, most often including yield quantity, quality, or aesthetics. Therefore, injury is centered on the pest and its activities, and damage is centered on the crop and its response to injury" (Pedigo 1989, p. 244).

As the concept is applied in terrestrial pest management, economic damage begins to occur when the cost of suppressing pest injury is equal to the potential monetary loss from a pest population. Pedigo (1989) further defines the term "gain threshold" as the beginning point of economic damage. The gain threshold can be expressed as follows:

$$\text{Gain threshold} = \frac{\text{Management costs (\$/acre)}}{\text{Market value (\$/bushel)}} = \text{bushels/acre} \qquad \textit{Equation 1}$$

Gain threshold is expressed as a unit of measure of the marketable product per a specified land area. Following from the previous example, if management costs for application of an pesticide are $10 per acre and the harvested product is marketed for $2 per bushel, the gain threshold would be 5 bushels per acre. In other words, at least 5 bushels per acre would need to be saved with a pesticide application for the activity to be profitable (Pedigo 1989, p. 245).

Pedigo (1989) defines another important damage level: the "damage boundary," which is defined as the lowest level of injury at which damage can be measured (Fig. 7.2). The level is reached before economic damage occurs and is a necessary complement to the idea of economic damage; i.e., no injury level below the damage boundary merits control, and injury estimated to result in economic damage does.

7.2.2 Economic Injury Level. Stern et al. (1959) first proposed the EIL and defined it as the pest level at which the cost of control is equal to the benefits derived by controlling the pest. Pedigo (1989) later suggested an alternative definition, in which EIL is the lowest number of pests that will cause economic damage. Simple terrestrial IPM models are based on knowledge of the market value of the crop, the population density of the pest, and the relationship between the density of the pest and the economic damage it causes to the crop. This can be expressed as:

$$P = \frac{C}{V \times D} \qquad \textit{Equation 2}$$

where P = density or intensity of pest population (for example, pests/acre)
C = cost of management per area (for example, \$/acre)
V = market value per unit of produce (for example, \$/acre)
L = loss per pest or the damage/density function (for example, (bushels/acre) divided by (pests/acre).

Note also that C and V are the same variables that define the gain threshold (Equation 1). The simplest EIL model therefore is :

$$EIL = P = \frac{\text{Gain Threshold}}{\text{Loss per Pest}} \qquad \textit{Equation 3}$$

Thus, the EIL population level is related to loss to the crop (per unit area) through the damage/density function, and to the ratio of the cost of pest control to the value of the crop (per unit area) through the gain threshold. A pest population is considered to cause an economic loss when its density equals or exceeds the EIL, and management activities are economically justified. Pest population densities below this level and whose potential growth will not allow them to reach this level are considered sub-economic and no management is advised (Fig. 7.1).

7.2.3 Economic Threshold. The economic threshold (ET) is probably the best-known term and most widely used index in making pest management decisions in terrestrial IPM. As described above, the ET is the population density at which control measures should be used to prevent an increasing pest population from reaching the EIL (Stern et al. 1959). Pedigo (1989) and others sometimes refer to it as the action threshold. Although originally Stern et al. (1959) expressed ET in pest numbers (or population density), the ET is really a time parameter, with pest numbers being used as an index for when to implement management (Fig. 7.3). That is, pest numbers are used as an indicator of that time when future pest injury is likely to cause economic damage (Hall and Norgaard 1973). If a pest population is growing as the season progresses, growth rates are predicted, and the ET is set below the EIL. By setting the ET at a lower value, one is essentially predicting that once the population reaches the ET, chances are good that it will grow to exceed the EIL. Therefore, it is appropriate to take action on an earlier date, before losses are incurred from reaching the EIL (Pedigo 1989).

The use of numbers as a temporal index requires substantial understanding of how a pest population is changing over time. Pedigo (1989) suggests that because we can rarely be certain about the population-time relationship, the ET always has been estimated and never calculated. Furthermore, because the ET is set (often arbitrarily) at a level other than the EIL, it is predictive; therefore, some degree of uncertainty (usually a great deal) is involved in its use (Pedigo et al. 1989). Contrary to Pedigo's comments, other researchers (Onstad 1987; Bechinski et al. 1989) suggest that ET can, in fact, be calculated. It remains to be seen, however, the extent to which can be achieved for burrowing shrimp populations.

From this discussion, it should be clear that the ET is a complex value. It is based on the EIL, a value of economics and a potential for injury, and it relies on an understanding of population dynamics of the pest. In instances in which the population dynamics of the pest species is poorly understood (i.e., population growth rate cannot be predicted), the ET may be set equal to the EIL or arbitrarily below it. An ET lower than the EIL has the great advantage of giving growers time to respond to a problem developing in a field or other habitat.

7.2.4 Calculation of Decision Thresholds. In developing economic indices for pest management decisions, the principal level to estimate is the EIL, because it includes the basic damage potential of a given pest population (Pedigo 1989). It can be used as the ET, or an ET can be determined from knowledge of the EIL and population dynamics. In either situation, the EIL must be known first (Pedigo 1989). The calculation of an ET for a pest is a continuing and site-specific process, because new values are required with changes in the input variables. Consequently, with changes in market values, management costs, and the susceptibility of the crop to damage, recalculation is necessary. Additionally, several EILs may be required to account for different cultural conditions, seasonal or annual changes in crop development, and consequential changes in susceptibility to the pest.

As discussed previously, the steps required to calculate the EIL are as follows:

1. Estimate the loss per pest or damage/density function *(L)*
2. Determine the gain threshold (Equation 1)
3. Calculate the EIL.

Of these steps, the first is by far the most difficult. Crude estimates of losses are usually obtained from field observation and experimentation with various-sized pest populations on a crop at specific times. Subsequently, yields are measured and losses caused by the pests are determined (See Pedigo 1989, p. 264 for an example). It should be noted that the damage/density function need not be linear and is, in fact, most likely to be non-linear (Onstad 1987).

7.3 LIMITATIONS OF THE BASIC EIL CONCEPT

Mumford and Norton (1984) suggest that the use of conventional EILs and ETs is "an operational, if not an ideal, decision rule." Its simplicity is one reason that the EIL concept has persisted for more than 25 years (Stefanou 1984). However, some authors have criticized the original EIL concept because it is too simple and overlooks the influence of other production factors that can affect the crop/pest system (Regev et al. 1976). It has also been pointed out that other important externalities are left out by the decision makers who use the original EIL concept. Such externalities include interseasonal dynamics, biological relationships with other pests and predators, environmental impacts due to control methods, resistance to pesticides, effects of control in neighboring fields, and health problems relating to pesticides (Regev et al. 1976). In addition, decision levels for management of some types of pests cannot be determined with EILs. Many vectors, medical pests, and pathogens often do not have a quantitative relationship between damage and injury. Consequently, they are not amenable to calculated EILs (Pedigo 1989). Finally, EILs are of limited use with preventative measures, such as host-plant resistance and most forms of ecological management (Pedigo 1989). Two of these shortcomings are discussed in more detail below.

7.3.1 Dynamics in Economic-Injury Levels. Early threshold models disregarded the dynamic nature of pest populations, product markets, pest costs, and efficacy (Harper et al. 1994). It is clear, however, that economic levels are very dynamic. They fluctuate with changes in costs, values, and production environments. The major forces behind change in economic decision levels, as shown in the previous equations, are 1) crop value, 2) management costs, 3) the degree of injury per pest, and 4) crop susceptibility to injury (Pedigo 1989).

Crop value is one of the most variable components of the EIL. It alone accounts for much of the change in EILs. The relationship between EIL and market values is inverse; as market values increase, EIL decreases and vice versa. As a general rule, estimates for EIL calculation are based on current or past records of crop value. Pedigo (1989) suggests that these values should be forecasted for the anticipated date of sale to reflect the expected increases or decreases in value. Note that the quality of a commodity may be of overriding importance in determining market values. In such situations, the value of the desired grade should be used in EIL calculations (Pedigo 1989, p. 250).

Management costs must be estimated before the wisdom of an action can be assessed. As management costs increase, the net benefit of control decreases. Consequently, EILs must be raised to accommodate the higher gain thresholds. Most years, management costs tend to be more stable than crop market values. These costs include labor, materials, and equipment. Management costs usually change gradually depending on inflation and are therefore reasonably predictable (Pedigo 1989, p. 250).

The degree of injury-per-pest is determined by both the pest and the host. For the purpose of calculation, injury-per-pest has usually been assumed to be linear. That is, injury is expected to double with twice as many pests. However, high densities have been shown to reduce injury-per-pest with some species because of interference between individuals and relative shortages of food. However, Pedigo (1989) recommends that unless there are other indications to the contrary, pests should be considered in an additive manner in estimating injury for EILs. Such an approach yields conservative estimates in decision making (Pedigo 1989, p. 255).

The relationship between injury and crop yield or utility is the most fundamental factor of the EIL. This relationship provides the biological foundation on which economic and practical constraints can be superimposed (Pedigo 1989). The four major factors involved in injury/crop-response relationships are 1) time of injury with respect to host growth, 2) type of injury; 3) intensity of injury, and 4) environmental influences on the host's ability to withstand injury (see Pedigo 1989, pp. 256-260 for more details).

Although the relationship among all these factors is relatively straightforward, complexity is evident when attempting to predict variability in the factors themselves. The primary factors are affected by complex secondary variables, such as the host-damage/pest-injury relationship, and tertiary variables, such as weather, soil factors, biotic factors, and the human social environment, that change the function of the secondary variables. Consequently, the primary factors are not simple constraints; rather, they are complex processes that operate through time (Pedigo 1989). Some authors (Harper et al. 1994) have attempted to develop frameworks for flexible ETs that can be implemented in the field. These thresholds take into account changes in economic and production conditions and the dynamic and stochastic nature of pest populations.

7.3.2 Environmental Costs. Another major shortcoming of the EIL concept receiving recent attention is that it does not explicitly address environmental concerns (Higley and Wintersteen 1992; Pedigo and Higley 1992) and, as such, does not take advantage of a means of decreasing pesticide inputs. That is, it does not account for the externalities associated with the use of pesticides.[1] The existence of externalities result in higher private levels of pesticide usage compared with the socially optimal levels. It has been recommended that in order to most efficiently use pesticides, the EIL must be elevated, providing incentives for less frequent treatment and acceptance of marginal increase in damage equal in value to the external costs imposed. EILs and other IPM criteria do not provide users with information on choosing the least environmentally hazardous pesticide when a pesticide must be used.[2] Expanding the EIL concept to take into account environmental risks is an important objective and has the potential to improve IPM decision making, potentially resulting in ever-decreasing pesticide inputs while maintaining production and profitability. Higley and Wintersteen (1992) point out that to include environmental risks in EILs, it is necessary to identify risks, rank their relative importance, and make a monetary estimate of the value of avoiding these risks. However, the estimation of environmental costs of pesticide use -- assigning monetary values to potential environmental hazards posed by a single pesticide application -- has been particularly difficult.

Over the years, various economic techniques have been developed to estimate the cost of nonmarket goods, such as environmental quality. Of the most common approaches (travel cost, hedonic price, and contingent valuation), only contingent valuation seems applicable to the problem of environmental costs associated with the use of a pesticide. The contingent valuation approach is a procedure for directly eliciting, through surveys, people's value of or willingness to pay for nonmarket goods. The legitimacy of contingent valuation for estimating costs of nonmarket goods has been debated recently; however, recent studies demonstrated that contingent valuation works as well as alternative methods. The first use of the contingent valuation approach in IPM was by Raupp et al. (1987) (although it was not identified as such). Other entomological studies that have employed contingent valuation to assess the value of managing medical insect pests include John et al. (1987) and Reiling et al. (1988).

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[1] Some authors (Pimental and Perkins 1989) suggest that IPM context implicitly does address environmental concerns. Simply because there is not an environmental component in the simple EIL equations does not mean that IPM practioners do not make allowances for environmental concerns. Those allowances come in many forms: the choice of specific pesticides, application method, timing, non-target considerations (drift), presence/absence of natural enemies, the pest/enemy dynamics, and so on.

[2] On the other hand, some authors (Pimentel and Perkins 1989) claim that IPM does provide contingencies on pesticide choice. For example, in the treefruit industry of Washington state, apple growers have been enjoying the rewards of successful IPM of mites as a result of the voluntary avoidance of pyrethroid insecticides, which are highly toxic to predatory mites. Many growers have not used a miticide in decades as a result. In this sense Higley and Wintersteen (1992) would have one believe that nothing has changed since the 1950s and 1960s. IPM, as practiced today, is actually fairly far advanced as far as environmental sensibility is concerned, and that is one of the fundamental reasons why it has endured and will continue to evolve as our understanding grows (T. Wildman, pers. obsv.).

More recently, Higley and Wintersteen (1992) have developed a model that considers the risks to various environmental categories by specific pesticides and assigns a cost to those risks. Environmental categories include specific aspects of water quality, effects on non-target organisms, and human health. Key elements of the model are that risks are determined by objective criteria and that the relative importance of risks to different categories and the monetary values of avoiding different levels of risk are estimated through a contingent valuation survey. This information is then used to calculate environmental costs for specific pesticides. The environmental cost data are used to calculate environmental EILs, which include both economic and environmental criteria for making management decisions regarding pests. The procedure is performed to:

- establish levels of risk (high, moderate, low, and none) for individual pesticides in specific environmental categories
- use a contingent valuation survey to determine the relative importance of each environmental category (the importance of an individual category divided by the total importance for all categories), and risk costs (the monetary value of avoiding high, moderate, and low levels of environmental risk)
- calculate the environmental cost of a pesticide in each environmental category by multiplying the relative importance for the category by the risk cost appropriate to the level of risk the pesticide poses to the category
- add the environmental costs for each environmental category to determine the total environmental cost of a given pesticide
- incorporate costs for each environmental costs into the conventional EIL calculation by adding environmental costs (*EC*):

$$\text{environmental } EIL = (PC + EC)/(VxL) \qquad \textit{Equation 4}$$

Higley and Wintersteen (1992) point out that establishing environmental costs is perhaps the most controversial aspect of their proposed method. The "true" environmental costs need to reflect the opinions of all of society. Presently, however, use of EILs is entirely voluntary. Therefore, establishing environmental EILs based on environmental costs that are greatly at odds with producers' views could diminish their acceptability and ultimately limit the use of environmental EILs. Consequently, Higley and Wintersteen believe that establishing environmental costs from producers' opinions is a necessary and appropriate approach. In fact, given that the current approaches to environmental risk assessment rely almost exclusively on "expert" opinion, it is believed that there is a place and need for broader perspectives on environmental risk (Higley and Wintersteen 1992). Results of the study performed by Higley and Wintersteen (1992) indicate substantial concerns by field crop producers regarding environmental hazards from pesticide use, so opinions of growers and the public regarding environmental risks may not be greatly different. They recommend that the only way to resolve this issue is to survey the public to estimate society's perception of environmental costs for a single use of a pesticide. Avoiding strategic and hypothetical biases in such a survey would be difficult, given that most people are unfamiliar with the use, risks, and economics of agricultural pesticides. If these biases can be avoided, however, any differences between producers' and the public's opinions regarding environmental costs could be quantified.

Higley and Wintersteen (1992) point out that when using the contingent valuation method to estimate environmental costs, survey responses will differ with geographical location. Therefore, additional surveys are necessary for a national use of this approach. Also, because pesticides and costs differ substantially among commodities, additional information would be needed before environmental EILs could be implemented for commodities other than field crops. Nor should agricultural groups be the only audience surveyed. Finally, since environmental cost estimates will vary through time, as a practical alternative to conducting annual surveys, environmental costs could be indexed to inflation and recalculated each year.

Pedigo and Higley (1992) point out a fundamental question with regard to environmental EILs: who should pay for them? They suggest two solutions: 1) consumers and farmers, who accrue the most benefits from pesticide use, should accept some costs associated with avoiding environmental injury, perhaps through emitter taxes, the costs of which would be passed on to the consumer; or 2) society should absorb costs of harmful effects of pesticide use (through subsidies or tax incentives) in order to maintain an abundant and inexpensive food supply. The alternative is, of course, to develop a system of cooperative use of elevated EILs. The ultimate solution to this question remains a subject of social and political debate.

Research into environmental costs associated with various control methods should be a high priority project. Note, however, that any esitmate of environmental costs may be highly contentious. A number of stakeholder groups may see these estimates as a threat to their livelihood. In addition, while models to estimate the monetary value of environmental damages exist, there is some debate within the academic community as to the reliability of estimates generated by certain methodologies under certain circumstances. This may add fuel to the fire of those that feel the addition of environmental costs to EIL will result in recommendations of unnecessarily lower level of pesticide usage.

7.4 STATUS OF BURROWING SHRIMP EIL AND ET MODELS

7.4.1 Model Selection. Review of the literature as well as discussions with oyster growers and other professionals in the area, suggested to us that although the use of EIL models could be useful to IPM in marine and estuarine aquaculture, there are no other examples of such application. Therefore, it was difficult to decide which model would be most appropriate for control of burrowing shrimp on oyster beds. Many aspects of the shrimp-oyster interaction and oyster culture operation are quite different than the pest-crop and crop-culture relationships found in terrestrial agriculture. For example, the damage done by the shrimp is incidental to presence of oysters in the system, because the shrimp are not deliberately attacking, feeding on, or competing with the oysters. Second, the duration of the interaction can cover 2 to 3 years and differs with location and the productivity of the waters.

At the outset of the study, we anticipated using terrestrial-agriculture EIL and ET models. We also recognized that these models might not be entirely appropriate, and thus designed our surveys and interviews to collect detailed information about the oyster growing and shrimp control process, including detailed economic data that might be useful in more complex models. However, it became apparent that the traditional models did not adequately capture the unique aspects of oyster farming and the interactions between burrowing shrimp and oysters. Some of these issues include the presence of mixed populations of pests, uncertainty about the damage/density function for either shrimp species and various aspects of oyster culture (e.g., seed-bed yield, fattening-bed yield, longline yield, etc.), seasonal changes in the impacts of the shrimp on oysters (e.g., low bioturbation in winter, high activity in summer), uncertainty of how to characterize or estimate seasonal changes in the impact of shrimp on oysters, and the fluid schedule oyster growers follow for setting seed, maintenance, transplanting, and harvesting.

7.4.2 Data. Twelve oyster growers from Willapa Bay and Grays Harbor were surveyed during in-person interviews and given a take-home questionnaire to fill out on their own regarding the economics of oyster farming and burrowing shrimp control. Six oyster growers returned the economic survey to Battelle. The economic data obtained from these surveys were of mixed quality. We were unable to collect a complete set of economic data in part because of the way we framed the questions. In many cases, the economic data that we requested exists; however, growers compile the information in a format different than the way we queried them.

Thus, there were significant inconsistencies in reporting, making it almost impossible to compare responses.

From the survey, we were able to derive an estimate for C, cost of management, or the cost of applying carbaryl to oyster beds. The mean annual value equaled $133.50 per acre (n=5), with a range of $112.55/acre to $150/acre. An add-on phone survey yielded an annual control cost estimate of $140/acre. The various components of the latter estimate were 1) $50/acre for 10 lb/acre of carbaryl applied at $5/lb (80% active); 2) $5 to $10/acre fee paid to Willapa-Grays Harbor Growers Association; 3) $70/acre for lease of helicopter services; and 4) $10/acre for burrow count survey. For the EIL model, we used the average value of $133.50.

Estimates derived from the survey of the annual market value of oyster production per acre ranged from $718/acre to $6,087/acre, with an average value of $3,314 per acre (n=6).[3] These figures were based primarily on annual yield reported in either gallons or bushels times the 1996 market price, ranging from $15 to $16/gallon. Growers reported average yields of 762 bu/acre (= 436 gal/acre) for bottom culture, and 274 bu/acre (= 156 gal/acre) for longline culture. The per-acre values derived from our survey vary markedly from those reported in Carkner and Harbell (1992). They report returns of $9,450 (675 gal/acre at 14/gal) for longline oyster production (3-year rotation) and $8,400/acre (600 gal/acre at $14/gal) for bottom culture oyster production (3-year rotation), generally much higher values than those reported in this study. This may be a result of lower reported yields from our survey (156 to 436 gal/acre) than those reported by Carkner and Harbell (600 to 675 gal/acre) for longline and bottom culture, respectively. Carkner and Harbell calculated yield and returns for fattening beds only, and it is unclear whether growers responding to our survey included acreage of both fattening and seed beds in their calculation of production per acre. Based on our survey, we estimated that the average market price for a bushel of oysters of $8.22/bu. This value was derived from the market value of oyster meat ($15.50/gal) multiplied by the average yield of meat per bushel (0.53 gal/bu) that oyster growers reported to us.

At this time, we have no estimates for the loss or damage/density function. As mentioned at the outset of this chapter, no reliable data exist for us to confidently determine the shape of this function, nor the boundary values. Without this information, it is not possible to

[3] There is a wide variation in the reported estimates of yield per acre. This is in part because of significant variation between the two primary growing techniques (longline and bottom culture) in volume of oysters harvested per acre. Other reasons are discussed in the text.

proceed with calculating the EIL. We cannot emphasize strongly enough how fundamental this information is to development of objective criteria for initiating burrowing shrimp control actions. The damage/density function should be estimated for both species of shrimp, in different substrate types, and for impacts to seed oysters, fattening bed oysters, and longline oysters. It seems likely that this function will be different for each of those scenarios.

7.4.3 Economic Threshold Model. The ET is based on the EIL and the growth rate of the pest population. Thus, without either an EIL model or an adequate burrowing shrimp population model (see Chapter 4), we cannot recommend an ET. Our inability to develop EIL and ET was not due to limited data on economic variables (cost of management and value of yield) but to lack of information on the actual injury caused by borrowing shrimp. In order to accurately estimate these models we need to develop a reliable damage/density function and a population growth model for burrowing shrimp. The lack of this fundamental information ultimately diminishes the utility of continuing the exercise of developing thresholds using the EIL or ET concepts.

7.5 RESERVATIONS ABOUT USING TERRESTRIAL MODELS FOR BURROWING SHRIMP IPM

Several authors have noted that few EIL and ET models have actually been developed, despite the existence of the model framework since the late 1950s (Pedigo 1989; Higley and Wintersteen 1992). The reasons so few models have been developed are because of the same difficulties as beset us: the lack of fundamental knowledge about the damage/density relationship, lack of an adequate population model for the pest, the presence of multiple pest species, and complexities in the culture of the crop and the interactions between the crop and the pest. As stated above, we have grave doubts about the utility of the basic EIL model, because it does not account for some of the important features of oyster culture and the interactions between oysters and burrowing shrimp. We were also hamstrung by the lack of quantitative information relating the loss of value of the crop to the density of the shrimp. We, therefore, cannot recommend the use of the EIL model described here. Furthermore, we believe that a new conceptual model, or a variant of the conventional model, is required for an EIL/ET model of the oyster-burrowing shrimp relationship. Finally, we strongly advise that no matter what model is selected in the future, rigorous field trials be conducted to demonstrate its predictability before it is recommended for decision-making.

Additionally, careful consideration should be given as to how the EIL and ET models will be used. To date, EILs and ETs have only been developed for pesticide application; they have not been used to guide the application of biological or physical controls, or changes in cultural practices (L. Higley, pers. comm.). Thus, oyster growers and environmental regulators should be cautious about using these models under new circumstances. One fundamentally important aspect of to keep in mind is that traditional EILs and ETs assume that the control practice can be implemented immediately upon the pest density reaching the ET. This would be true for terrestrial application of pesticide, but not necessarily for the estuarine setting where environmental and regulatory considerations can delay the opportunity to implement control tactics for several months. Thus, this time lag needs to be incorporated into the ET model.

The fundamental difference between the simplistic EIL/ET models discussed above and the models that are ultimately needed for burrowing shrimp on oyster beds is the issue of incorporating environmental costs and benefits resulting from control of the pests (i.e., the externalities of shrimp control). In estuaries, farmers share certain ecosystem goods and services (such as clean water, plankton, finfish predators) with other stakeholders (i.e., commercial and recreational fishers, land owners and private citizens, resource agencies), and concern about potential impacts of shrimp control to these resources underlies the regulation of carbaryl and the need for an IPM plan. At the same time, oyster farming and control of burrowing shrimp (particularly ghost shrimp) provides benefits to estuarine goods and services (i.e., through promotion of clean water, creation of habitat for crabs, increasing biodiversity of benthic invertebrates). Thus, both the costs and benefits of control practices must be included in the EIL.

EIL models that exist for terrestrial agriculture are not widely used, and the oyster-burrowing shrimp system presents a host of unique and poorly understood properties which prevent us from developing appropriate EIL or ET models at this time. It is therefore not possible for us to recommend a economically-based decision threshold at this time. However, it is clear that development of such a model should be a high priority for the rational management of burrowing shrimp on commercial oyster beds.

7.6 Other Approaches for Setting Thresholds

As discussed above, EILs and ETs have never been developed for pest control practices other than pesticides (L. Higley, pers. comm.). Despite this, growers use some type of criteria to decide when to implement other methods of controlling pests. Usually the grower or IPM consultant will use a "rule of thumb" based on experience with the pest and effectiveness of the control agent under specific cultural and environmental conditions (T. Wildman, pers. obsv.). In these cases, IPM becomes a philosophy and an art, rather than a rigorous science, in which growers use their best professional judgement to choose the most effective and economical method available that will not jeopardize other goals. For example, to control one pest on a crop, the grower might elect to create habitat for a natural predator of the pest rather than use an insecticide because the chemical might harm the predator. Later in the year, the grower might elect to use the pesticide because the predators and other susceptible non-target species are no longer present. Such decisions seem adequate and based on common-sense, but they are not necessarily made with rigorously objective criteria, nor are they the only possible decisions. However, objective guidelines for making these complex decisions are lacking. A fundamental challenge for the science of IPM is to develop a process for addressing these real-world complexities.

7.7 Sampling Plan For Burrowing Shrimp in Oyster Beds

The goal in developing a sampling plan is to construct a method that growers can use to determine how many pest organisms are present and whether this number of pests equals the economic threshold (ET). Thus, the sampling plan becomes the method by which the decision criteria (discussed in previous sections) is implemented by the grower. In this chapter, we evaluate two approaches for developing a sampling plan for burrowing shrimp in oyster beds. This exercise demonstrates the manner in which a final sampling plan would be developed once accurate census methods and control-treatment decision criteria (EIL/ET) for burrowing shrimp are established.

We investigated two basic approaches to developing a sampling plan, sequential-number and fixed-number sampling plans, which are widely used in other IPM strategies (T. Wildman, pers. obsv.). In sequential-number sampling plans, census samples are taken continuously until pest densities exceed some critical threshold, or until sufficient number of samples have been collected to assure that the true density of pests is below the threshold. In fixed-number sampling plans, a set number of census samples is collected at each census interval to determine whether the mean density of pests exceeds the critical threshold. In general, the number of samples that is required under either sampling plan is affected by the spatial variability in the density of the pests: the higher the variance in pest density is relative to the mean pest density, the more samples will be required to achieve or maintain the same level of precision.

By way of analogy, consider if one were to sample an orchard to determine the number of trees per acre. Because orchards are planted in a uniform manner, the trees are evenly distributed and only one sample (if it is large enough) is required to determine the population. However, consider the case if the trees in a forest were to be sampled to determine that population size. A greater number of samples would be required, caused by the random and/or clumped manner in which trees naturally grow, to achieve the same level of precision as the orchard sample. Finally, consider the spatial distribution of insect or crustacean pests that are difficult to see because of their size and reclusive habits. Their distributions may be clumped, evenly-spaced (perhaps caused by territorial behavior), or randomly distributed across the landscape of the crop. Furthermore, this distribution could change seasonally or as pest population size changes. If the pests are not easily seen, and the form of their spatial distribution is not known, then censussing their populations haphazardly could be highly inaccurate. These examples illustrate why the variance in the abundance and spatial distribution of the pest species is so important in devising a sampling plan.

Precision is usually defined as plus or minus some measure of variation around the estimate of the mean at a certain probability level. For example, suppose a sampling plan indicates that if 50 samples are taken, the estimate of the mean will be within plus or minus 20% of the true mean with 90% probability. Therefore, if 50 burrow count samples are taken from an oyster bed and the calculated mean is 10 b/m^2, with 90% confidence, the true mean number for the population in that bed lies within the range of 8 b/m^2 and 12 b/m^2.

Taylor's power law (TPL) is useful for estimating the relationship between the mean and the variance (Southwood 1978). It describes the relationship between the mean and variance as the following:

$$v = am^b \qquad \textit{Equation 5}$$

where
v = the variance
m = the mean
a = the intercept, and
b = the slope of the line.

This relationship becomes a straight line when the mean and variance are converted to natural logs:

$$\ln(v) = \ln(a) + b \ln(m) \qquad \textit{Equation 6}$$

In practice, the means and variances from field counts are log-transformed and linear regression is used to estimate "v."

We analyzed historical burrow-count data that had been used by WDFW to evaluate whether commercial oyster beds could qualify for carbaryl treatment. These data were collected by Dennis Tufts, who provided a copy of his field notes, which contained the raw data from all site inspections. Initially, these burrow-count data were analyzed in two ways: first with the individual-bed means and variances and then by combining counts from several beds into one mean and variance. The linear regression of the individual beds was $\ln(v) = -1.805 + 1530 \ln(m)$, with $r^2 = 0.272$ (df = 94). The low r^2 value indicates a poor relationship between the mean and the variance, which was probably a result of the low numbers of quadrats having been collected on each bed.

In the second analysis, beds were grouped by mean burrow counts into 12 sets: 11.6 b/m^2 to 15 b/m^2, 15 b/m^2 to 20 b/m^2, 20 b/m^2 to 25 b/m^2, etc... up to 73 b/m^2, which was the highest density recorded. Thus, there were 12 pairs of means and variances, and the regression analysis was repeated. The results were: $\ln(v) = -2.272 + 1.704 \ln(m)$, with $r^2 = 0.713$ (df = 10). This was a much better statistical fit than the analysis of individual counts, but not as good as what was hoped.

One good sign was that the y-axis intercepts and slopes were similar in value, which indicates that grouping the data from different oyster beds did not substantially change the relationship between the mean and variance. Grouping the data did reduce the variation around the regression line, but not sufficiently to justify proceeding further with development of a sequential sampling method at this time.

Finally, a fixed-number sampling plan was calculated using the TPL data from individual beds and from the grouped data. The results from this analysis were encouraging. The formula for the fixed-number sampling plan is:

$$n = (t^2 \div d^2) \times (v \div ET^2) \qquad \textit{Equation 8}$$

where n = the number of burrow-count samples

t = Student's t

d = percentage of error as a decimal

v = the variance estimated from TPL

ET = Economic Threshold, or mean critical density (Ruesink and Kogan 1975).

For this analysis, a 5% probability level, t = 1.96, d = 0.20, and ET = 40 b/m^2 were used. The value of 40 b/m^2 was chosen for demonstration purposes. For individual beds, v = 46.47, and for the grouped data, v = 55.3. Therefore, using TPL for shrimp in individual beds, 3 samples (rounded from 2.785) would be required. Using the TPL from grouped data results in 4 samples (rounded from 3.323). Thus, at an ET of 40 b/m^2, a worker taking counts from four 1-m^2 quadrats would have 95% confidence that the estimate of the mean density is within 20% of the true mean density in that bed.

In this example, the combination of low variance and large critical density (40 b/m^2) results in the small sample size. The low number of samples gives some leeway to counteract the poor fit to TPL. For example, it would be prudent to recommended that 8 to 10 samples be taken per bed to ensure a high degree of confidence that the resulting estimate of mean burrow-count density would achieve sufficient precision to make defensible decisions about burrowing shrimp control. From personal experience, 8 to 10 burrow-count quadrats could be counted within 60 min, depending on the distances separating the placement of each quadrat. Note that, from Equation 6, as the critical density (ET) decreases, the number of samples to count (sample size) increases. For example, for ET = 20 b/m^2, thirteen quadrats per oyster bed would be required to achieve the same precision that 4 quadrats provide when the ET = 40 b/m^2.

An additional consideration is the how the population sampling effort should be dispersed over the oyster bed. Ideally, the samples should be taken from different areas on each bed so as to adequately characterize the burrowing shrimp population over the entire bed. Clearly, if the sampling effort was limited to one portion of an oyster bed, a grower would have incomplete information about the densities of burrowing shrimp at more distant points on the bed. Furthermore, since oyster beds are usually irregular in size and of widely differing areas, the location of sampling sites must be tailored to each bed. The analysis presented above did not take into account the size or shape of the oyster bed because appropriate data were not available (i.e., variability in burrow density [or shrimp density] as a function of spatial scales from one acre to multiple acres). However, as a starting point, and using the example discussed above, we would recommend that 8 to 10 quadrats be taken per acre and that each sample be taken ~50 ft apart.

At this point, it is doubtful that any further combinations or grouping of the existing data will improve this sampling plan. It is fortuitous that the analysis supported using a fixed-number sampling plan, as it is simpler to implement than a sequential sampling plan. As noted at the start of this chapter, the WDFW data set upon which this analysis was based contains burrow-count data that were collected during early spring when the relationship between burrow-count density and the density of burrowing shrimp can be quite poor. However, this data set was the best one available for this analysis. Thus, the results from this analysis should be viewed only as demonstrative of the process to obtain a sampling plan. After a more reliable population censussing method is established, and once the ET is estimated, this analysis should be repeated to determine the minimum number of census samples needed to accurately estimate burrowing shrimp abundance. Note also that if separate ETs are calculated for different species, habitats, or aspects of oyster culture, separate sampling plans will have to be generated.

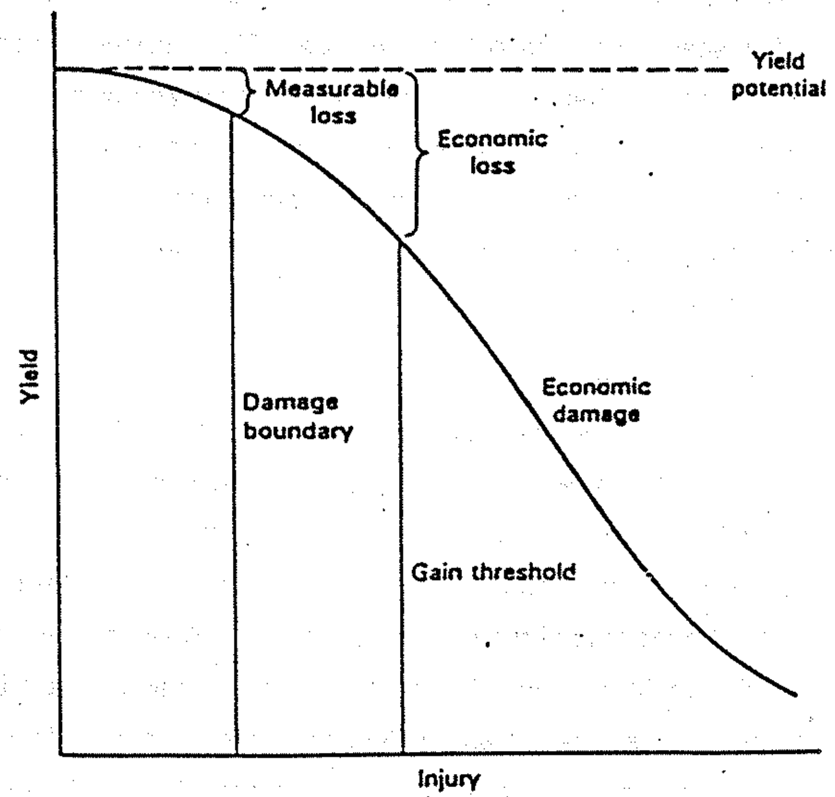

Figure 7.1. Diagram showing relationship of the damage boundary to economic loss and the gain threshold. (From Pedigo 1989).

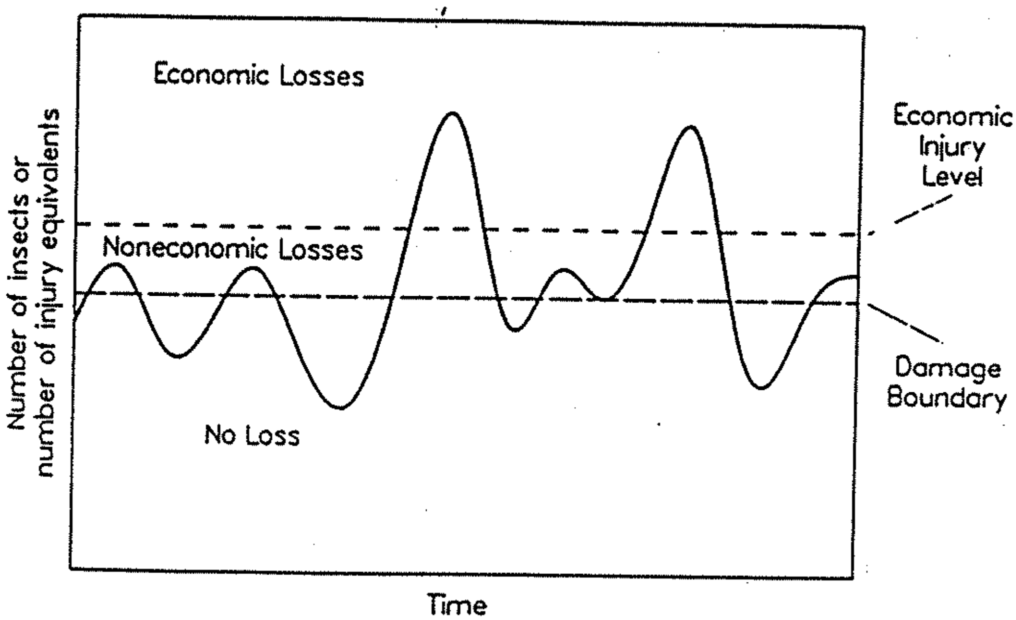

Figure 7.2. Diagram showing relationship of the damage boundary to the economic-injury level. (From Pedigo 1989).

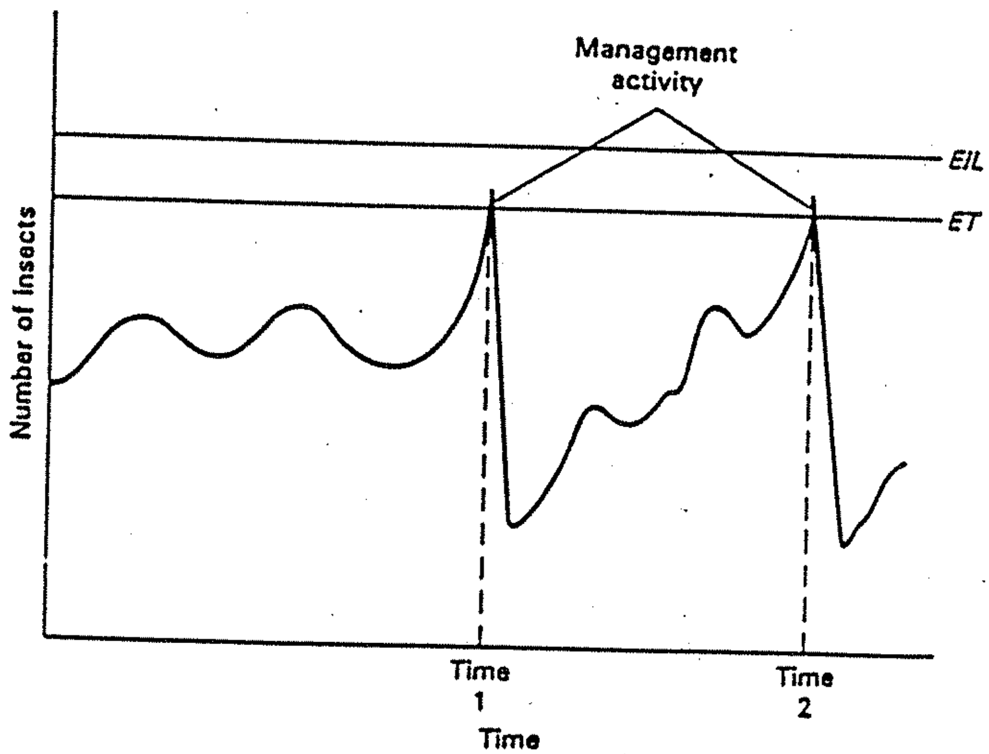

Figure 7.3. Diagram showing relationship of the economic threshold to the economic-injury level and time of taking action. (From Pedigo 1989).

8.0 IMPLEMENTING THE IPM PLAN

An IPM plan to manage damage caused by burrowing shrimp to oyster crops ideally should contain all of the following elements: 1) knowledge of the population biology of the shrimps and of the natural ecological factors that control their abundance and distribution, and models to project their future population size in an oyster bed; 2) an integrated array of control tactics and cultural methods that can be used to reduce the size and growth rate of burrowing shrimps while simultaneously minimizing risk to (or even enhancing) other natural resources; 3) use of accurate, scientifically based, and objective criteria for making decisions about when and where to deploy control tactics; and 4) accurate census methods and appropriate sampling plans for monitoring changes in ghost- and mud-shrimp population sizes relative to critical threshold densities at which control tactics need to be applied. In this chapter, we discuss the status of an IPM plan for burrowing shrimp, suggest ways to implement the IPM plan when one is ready, identify and prioritize critical information gaps and research needs, and provide guidelines for periodically updating the IPM plan.

8.1 STATUS OF THE IPM PLAN

Some of the elements needed for an IPM plan are currently available, but critical information is currently lacking that prevent a "true" IPM plan from being developed. As is summarized below, much is known about the ecology of burrowing shrimp and methods of culturing oysters, several methods of controlling burrowing shrimp have been suggested and evaluated in the field (although not all with scientific rigor), and guidelines have been provided for conducting benefit/cost evaluations of control methods and for developing sampling plans to monitor populations of the shrimp. However, methods currently used to measure burrowing shrimp densities on oyster beds are inaccurate and need to be revised, and it is not presently possible to forecast changes in the abundance of the pests. The relationship between the density of shrimp and the damage they cause to oysters is very poorly characterized. It is therefore not possible to develop objective criteria with which to determine when and where to apply control tactics, and new economic injury models for making such decisions must be developed. Although few control methods have been rigorously tested in the field, farmers' have tested several approaches informally, and the only method that has been shown to work consistently and economically is aerial application of the pesticide carbaryl. Thus, an IPM plan for burrowing shrimp is still a long way from being ready. These issues were developed in the preceding chapters and are summarized below, followed by recommended actions to address the work needed to develop an IPM plan.

In the interim, there is much the stakeholders can do to progress toward an IPM plan. In addition to the recommendations outlined in Section 8.3, growers and regulators can take the following immediate steps. Growers should:

- be more rigorous in collecting information on the costs to farm each of their beds and the yields recovered from each bed,
- track the abundance of burrowing shrimp on each bed, noting the relative abundances of both species, and monitor changes in the coverage of eelgrass on these beds;
- investigate methods of ground application of carbaryl, including border treatment and more accurate delivery to shrimp burrow openings; and
- investigate the integrated control practices suggested in this report.

State and Federal regulatory agencies should:

- reduce the bureaucracy associated with carbaryl spray permits so that the permit-evaluation process is shortened. If growers could submit their applications in mid-June, they could conduct the census of shrimp burrows in May which would provide a more accurate estimate of shrimp density;
- help growers to develop alternative strategies for controlling burrowing shrimp by easing restrictions on tideland habitat manipulations on specific oyster beds as appropriate. Many growers expressed the concern that their investigation of alternative control methods were hampered by such restrictions. Easing restrictions on a limited number of beds, while monitoring the efficacy of shrimp control and impacts to estuarine resources, could provide growers with an incentive to conduct such studies.
- continue to support research into development of alternative control methods, improved shrimp census methods, the damage/density relationship between oysters and burrowing shrimp, and development of scientifically-sound decision criteria.

Dialog between growers, regulators, the local community, and other interested people must continue, and efforts must be re-doubled to increase trust among these parties. All of these parties seem to share a serious interest to reduce the economic impacts of burrowing shrimp, and maintain a sustainable oyster industry and a sustainable estuarine ecosystem. However, mistrust and lack of communication hinders progress toward these goals (Eng 1996). Forums such as the Burrowing Shrimp Advisory Committee provide an excellent opportunity for stakeholders to communicate their concerns and work on improving their inter-relationships.

8.2. SUMMARY OF FINDINGS

8.2.1 Ecology of Burrowing Shrimp We reviewed the population biology (life history, recruitment, measurement, and modeling thereof), factors that regulate distribution and abundance, and impacts on other benthic organisms (including oysters) of two species of burrowing shrimp, *Neotrypaea californiensis* (ghost shrimp) and *Upogebia pugettensis* (mud shrimp). The two shrimp have different life histories (i.e., timing of reproduction, timing of recruitment, growth rates, and probably natural mortality rates), different habitat preferences (i.e., ghost shrimp are more abundant in higher salinity, sandier environments; mud shrimp are more abundant in lower salinity, muddier environments), have different burrowing and feeding habits (though the latter is debatable), and they have different effects upon other benthic organisms, such as oysters (i.e., ghost shrimp cause more damage to oysters than do mud shrimp). However, efforts to control these species treat them as if they were one species and do not take use knowledge of their ecologies to develop targeted control tactics.

The abundance and distribution of the shrimp (particularly ghost shrimp) can be significantly affected by salinity, shell substrate, and predators (especially staghorn sculpin and Dungeness crabs). There are suggestions that dense stands of eelgrass and interspecific competition between the two burrowing shrimp species can also inhibit population growth or recruitment of ghost shrimp. Studies on processes that regulate shrimp colonization of oyster beds, their interactions with eelgrass, and processes that affect the abundance of predators and rates of predation would provide information useful for enhancement of natural processes to control burrowing shrimp.

Ghost shrimp cause more damage to oyster culture operations than do mud shrimp, but at very high densities, mud shrimp also cause damage to oyster yields. The predominant mechanism of damage to oysters is by burial caused by sediments resuspended by the shrimp during burrow excavation and feeding. Oyster growers and naturalists from Willapa Bay and Grays Harbor recount that burrowing shrimp populations have increased dramatically since the 1940s, but no quantitative records could be found for independent verification. No studies have been conducted to determine whether or why this population increase occurred, although a number of mechanisms have been suggested. Understanding why burrowing shrimp populations have increased could yield fundamental insight about methods to control the shrimp within the two estuaries.

The most widely used method of measuring the abundance of burrowing shrimp on oyster beds (i.e., counts of burrow openings within fixed-area quadrats) lacks scientific rigor and likely provides incorrect estimates of shrimp abundance. Burrow counts made during early spring (before May) are poorly correlated to the true density of the shrimp. Additionally, it is not possible to accurately determine the relative abundances of the two shrimp species using the burrow count census method. Consequently, existing data are inadequate to determine the relationship between the density of shrimp and damage to oyster crops or to predict rates of shrimp population growth. We describe three approaches to develop population models for burrowing shrimp, and we recommend that a simple population model should be developed that would provide oyster growers and resource managers with scientifically-sound means to forecast when oyster beds will require treatment to control burrowing shrimp.

Lack of these tools and knowledge profoundly affect attempts to predict future densities of the burrowing shrimp and to evaluate whether an oyster bed is threatened with economic damage from the shrimp. The consequences of these problems ripple through the IPM plan and encumber the ability to set criteria and thresholds to initiate control tactics. Clearly, studies are needed immediately to develop accurate population census methods, develop models to forecast population growth rate, and to measure the relationship between the density of each shrimp species and damage to oysters.

8.2.2 Oyster Culture We reviewed the major methods used to culture oysters in different parts of the world and evaluated which ones were practical for use in culturing Pacific oysters (*Crassostrea gigas*) in the Willapa Bay and Grays Harbor estuaries. We also evaluated the vulnerabilities of each culture method to damage from burrowing shrimp. The major methods include bottom culture, floating culture, stake culture, and rack culture. The latter three methods suspend oysters above the substrate, thereby reducing the direct interaction between burrowing shrimp and the bivalves. Each method has several variants; for example, rack culture includes longline culture and rack and bag culture. Bottom culture, longline culture, rack and bag culture, and stake culture are the methods currently used in Willapa Bay and Grays Harbor.

Although floating culture would be much less affected by burrowing shrimp than any of the other oyster growing methods, floating culture is not practical for Willapa Bay or Grays Harbor because of the paucity of deep water (required to keep lines of oysters above the substrate) and the vulnerability of floating systems to damage from storms. Longline culture is constrained to high-productivity, mid- to low-intertidal ground because workers must be able to access the oysters on foot and transferring oysters between beds is impractical. Longline culture (and other rack culture methods) are vulnerable to burrowing shrimp that can undermine posts supporting the lines of oysters, soften the substrate, thereby hindering access to the oysters, and bury oysters that fall off lines (up to 50% of the crop falls off lines and is grown and harvested as bottom-cultured oysters). Rack and bag culture might use a slightly wider range of oyster grounds than can longline culture because oysters can be transferred between beds, but the necessity of keeping the bags supported above the sediment constrains rack and bag culture to a smaller range of tidal elevations than that used by bottom-culture methods. Rack and bag culture is also vulnerable to burrowing shrimp damage caused by their softening of the substrate, which can cause the racks to sink into the sediment and can hinder access by workers on foot to the cultures. Bottom culture is the most economical method of growing Pacific oysters. With the ability to transfer oysters between beds mechanically or manually, bottom culture can use lower-productivity ground for growing seed and premium-productivity ground for producing marketable oysters. Thus, bottom culture can make use of a wider range of tide flats in Willapa Bay and Grays Harbor than can the off-bottom culture methods, which would appear more practical. However, bottom culture is also more vulnerable to burrowing shrimp damage than the other culture methods because the oysters are grown directly on the sediment surface, and thus can sink into the softened substrate or be buried by sediments resuspended into the water column by the shrimp.

8.2.3 Control Methods. We reviewed and evaluated 15 chemical, biological, and physical methods of controlling burrowing shrimp and cultural methods of minimizing their damage to oyster crops, and suggested several means of integrating control and cultural methods to decrease damage caused by burrowing shrimp to oysters. Very few rigorous or quantitative studies have been conducted to measure the efficacy or costs and benefits of the control methods (with the exception of carbaryl pesticide). Evaluation of the other methods was based on interviews with oyster growers and knowledgeable experts, published research on related topics, and our own professional judgement. Several methods were considered to be technically infeasible or impractical: development of silt-resistant oysters, release of parasites and pathogens of shrimp, release of sterile male shrimp, bioengineering faulty genes into the burrowing shrimp population, use of explosives, and growing oysters with floating culture methods.

The only proven method for controlling burrowing shrimp on commercial oyster beds is the pesticide, carbaryl. However, several methods show some promise, but need additional research and field trials before they could be used on a commercial scale. These include other pesticides (such as abamectin and imidacloprid), predator enhancement, shell pavementing, sediment compaction or sediment disturbance (i.e., harrowing or dredge harvesting), and sediment barriers. Cultural methods that might reduce economic damage to oyster crops include reinforcement of longline structures, harvesting of burrowing shrimp, and culture of other species that are more tolerant of burial and softened sediments (such as Manila clams). As with many of the potential control methods, these cultural practices have yet to be demonstrated to be economically feasible on a commercial scale.

Oyster growers and non-grower experts (academic, public-sector, and private-sector estuarine ecologists, government regulators, resource agency representatives, and natural resource harvesters) evaluated several control methods for long-term, non-target impacts to environmental and human resources. As a whole (and acknowledging that the ratings were not unanimous), the growers and other experts felt that carbaryl pesticide, predator enhancement, and shrimp harvest would have either no long-term detrimental impacts or long-term beneficial impacts to environmental and human resources. All other methods were viewed as potentially having long-term, negative impacts on one or more resource category; however, most were viewed as having either no-effect or beneficial effects on most resource categories. Methods that were judged to have the greatest potential for long-term negative impacts were other pesticides, sediment barriers, clay injection, water jets, and electroshocking/ultrasound. Not all possible control methods or cultural practices were included in this evaluation because some were considered to be too impractical (listed above) and others we learned of after this evaluation was completed. These latter methods were dredge harvesting, diking and damming, reinforcement of longline structures, and alternative crops.

Based on these evaluations, we conclude that carbaryl pesticide is an effective and reasonable control method, but that studies should be conducted to increase the precision of delivery and reduce application rates. Furthermore, we conclude additional research is needed to evaluate other promising control methods, such as shell pavementing, dredge harvesting, sediment compaction, and other pesticides. Incentives may be needed to encourage growers to try these methods on their oyster grounds. Oyster growers and resource agencies should actively support efforts to conserve and enhance natural populations of finfish predators of burrowing shrimp, such as sturgeon, salmonids, and staghorn sculpin. Oyster growers and other entrepreneurs could investigate expansion of existing markets or creation of new markets (such as seafood products) for burrowing shrimp themselves. We suggest several ways in which control methods and cultural practices might be integrated and recommend that studies be conducted to investigate their efficacy and practicality; however, virtually no studies have been conducted to evaluate the effectiveness of these integrated methods, and we recommend that research be conducted to investigate their efficacy, economic practicality, and environmental benefits and costs.

8.2.4 Decision Criteria. The current threshold for application of carbaryl to control burrowing shrimp on oyster beds (burrow hole count of 10 b/m^2) has been used since the 1970s. However, we found that the basis for this threshold is seriously compromised for biological and institutional reasons. First, the burrow-count data are collected in early spring when the relationship between the number of burrows and the abundance of burrowing shrimp is highly unreliable. Dumbauld (1994) showed that, between early spring and in summer, the density of burrows on a bed can change two- to six-fold, even though the true abundance of shrimp did not change. The need to sample in the early spring is a consequence of institutional requirements: growers must collect these data in early spring in order to submit applications for carbaryl spray permits by May deadlines imposed by regulatory agencies. Second, the relationship between the density of burrowing shrimp and damage to oyster crops has not been quantified. Third, the threshold does not distinguish between the numbers of burrows made by each of the two species of shrimp, yet growers and biologists suspect that oyster yields are less affected by mud shrimp than by ghost shrimp. Thus, the threshold of 10 b/m^2 is not an accurate predictor of the damage that burrowing shrimp cause to oyster crops and is inappropriate for use as a decision criterion.

We were unable to estimate treatment thresholds using EIL or ET models for two reasons. First, there are critical knowledge and data gaps that hinder using existing EIL and ET models, including lack of information about the relationships between burrowing shrimp densities and the economic impacts to the oyster bed (i.e., the damage/density function, which is needed for the EIL model), and the lack of adequate data to develop a rigorous burrowing shrimp population model (needed for the ET model). Second, the EIL and ET models developed for terrestrial IPM plans cannot be directly applied to the oyster-burrowing shrimp scenario because of unique aspects of the interactions between the ecology of the shrimp and the culture of oysters. These include the multiple-year growing period for oysters, the influence of seasons on shrimp and oyster physiology and behavior, the influence of substrate-type on the interaction between shrimp and oysters, and the variable schedule growers follow to grow and harvest oysters. Furthermore, traditional terrestrial EIL and ET models do not include consideration of the costs of the control methods to other environmental resources and services, which are highly valued within the Willapa Bay and Grays Harbor estuaries.

We demonstrated how to develop a sampling plan, which would be the tool used by oyster growers or regulators to implement the EIL and ET models. Using the WDFW burrow-count data set, we determined that a fixed-number sampling plan could provide the necessary precision to determine whether burrow densities equaled or exceeded some threshold density. However, as the WDFW data set has numerous inaccuracies, our analysis should be used only as an example of the process to develop a sampling plan. Once better methods are developed to census populations of ghost and mud shrimp, and once decision criteria are established for the control methods (for example, an ET model), a formal sampling plan could be developed using the process we describe. Separate sampling plans will be necessary if distinct control thresholds are established for each species of burrowing shrimp and for different aspects of the oyster farming (i.e., seed beds, fattening beds, longline culture, rack and bag culture).

8.3 SUMMARY OF RECOMMENDATIONS

8.3.1 Ecology of Burrowing Shrimp

- Current pest management practices treat the two species of burrowing shrimp as if they had the same ecologies and impacts, yet biologists and growers know the two species are different in these respects. Separate pest management strategies should be developed for each species, or that at least take into account critical differences between them, such as timing of recruitment and impacts to oysters and eelgrass.
- Understanding why burrowing shrimp populations have increased since the 1950s could yield fundamental insight about methods of controlling the shrimp within the two estuaries. It is likely that the responsible process(es) operate on a regional scale.
- Studies on processes that regulate shrimp colonization of oyster beds, their interactions with eelgrass, and processes that affect the abundance of predators and rates of predation would provide information useful for enhancement of natural processes to control burrowing shrimp.
- Studies are needed immediately to develop accurate population census methods, develop models to project population growth rate, and to measure the relationship between the density of each shrimp species and damage to oysters. We recommend that efforts be directed toward development of demographic models that can be used to forecast future population densities of shrimp on individual oyster beds, given site-specific information about the existing populations and rates of recruitment.

8.3.2 Oyster Culture

- We concluded that bottom culture, longline culture, rack and bag culture, stake culture, and other variants of rack culture were the best methods to use in Willapa Bay and Grays Harbor on the basis of the physical constraints imposed by the bathymetry of the estuaries and the frequency of strong storms that hit the coast.

- Although floating culture would be much less affected by burrowing shrimp than any of the other oyster growing methods, floating culture is not practical for Willapa Bay or Grays Harbor because of the paucity of deep water (required to keep lines of oysters above the substrate) and the vulnerability of floating systems to damage from storms.

- Longline culture operations could reduce some risk of damage from burrowing shrimp by reinforcing the structures (i.e., increasing the length of posts, the depth they are pushed into the sediment, strengthening the attachment of lines to the posts, and reducing the spacing between posts).

8.3.3 Control Methods

- We concluded that carbaryl pesticide is the most effective and economically practical control method currently available, but that studies should be conducted to evaluate other control methods and the integration of potential control methods.

- The amount of carbaryl that is used to control shrimp might be reduced by increasing the precision of delivery, such as by ground delivery. Studies are needed to investigate alternative carbaryl delivery systems and to evaluate the benefits and costs of applying carbaryl in spring or fall, particularly just after recruitment of young-of-the-year shrimp.

- Promotion of eelgrass growth on or adjacent to oyster beds might benefit oyster culture by providing refuge habitat for predators of burrowing shrimp. However, eelgrass can interfere with mechanical harvest of bottom-cultured oysters. Growers need incentives to promote eelgrass growth on their private property; possibilities include funding research to develop oyster farming tools, machinery, or practices that are more compatible with eelgrass, property trading or purchasing, and tax incentives.

- Oyster growers and resource agencies should actively support efforts to conserve and enhance natural populations of finfish predators of burrowing shrimp, such as sturgeon, salmonids, and staghorn sculpin.

- Oyster growers and other entrepreneurs should investigate expansion of existing markets or creation of new markets (such as seafood products) for burrowing shrimp.

- Several control methods deserve further investigation, using new techniques or timing of application. These include shell pavementing, dredge harvesting, sediment compaction, and other pesticides. Rigorous scientific studies should be designed to evaluate the efficacy, costs, and non-target impacts of these methods.

- We suggest several ways in which control methods and cultural practices could be integrated and recommend that studies be conducted to investigate the efficacy, costs, and non-target impacts of these practices. The following are reviewed integrated methods:

  - shell pavement and predator enhancement,
  - chemical control and predator habitat enhancement,
  - chemical control and shell pavement,
  - chemical control and physical barriers,
  - coordination of control actions (chemical, biological, or physical) with recruitment of shrimp,
  - sediment compaction (or harrowing) and shrimp harvesting or predator enhancement,
  - predator habitat enhancement and cultural practices,
  - diking and damming and predator enhancement,
  - diking and damming and low salinity, and
  - harrowing and low salinity.

- Growers may want to use the benefit/cost guidelines we provide to evaluate new or integrated control methods.

8.3.4 Decision Criteria

- The existing decision criterion used to determine which oyster beds qualify for carbaryl treatment (i.e., burrow counts $\geq$ 10 b/m^2) is not an accurate predictor of the damage that burrowing shrimp cause to oyster crops, and is thus inappropriate for use as a decision criterion. Studies should be undertaken immediately to resolve these problems. The research should identify accurate methods to census shrimp populations, develop population models for ghost and mud shrimp, and quantitatively characterize the damage/density relationship between oyster yield and burrowing shrimp density.

- Objective decision criteria should be based on EIL/ET models. These models will require accurate methods to census the pest populations and quantitative characterizations of damage/density functions. Unique EIL/ET models must be developed for burrowing shrimp on oyster beds that account for the temporal complexities of oyster culture and ecology of burrowing shrimp, fluctuations in production costs and market values of the product, and the costs of control tactics to environmental resources and services.

- It is likely more than one EIL/ET model (and, consequently, more than one critical threshold) will be required to characterize the oyster-shrimp-control interactions for different aspects of oyster culture (i.e., seed beds, fattening beds, longline beds, rack and bag beds). These will provide oyster growers and environmental regulators with greater flexibility in deploying and managing control tactics.

- Once methods are developed for accurately censussing burrowing shrimp populations and decision criteria are developed for deployment of control tactics, sampling plans can be developed following the process described in this chapter. If separate decision criteria are developed for the major aspects of oyster culture, then separate sampling plans are likely to be needed to support each critical pest threshold (i.e., for seed beds, fattening beds, longline beds, and rack and bag beds). The sampling plans must take into consideration the size and shape of oyster beds to ensure that sampling sites are distributed across the whole bed, thereby accurately characterizing the abundance of ghost and mud shrimp.

8.4 CRITICAL INFORMATION AND RESEARCH NEEDS

Throughout this report, we have identified topics and issues in which additional information is needed to make the IPM plan work. Below we identify those issues that we feel are most crucial for the success of the IPM plan. The first section identifies the five most critical needs, and briefly outlines approaches to obtaining the necessary information. After that, we briefly outline the topics requiring further study within each of the major subject areas discussed in this report.

8.4.1 The Five Most Critical Needs Based on their impacts to the development and implementation of an IPM plan for burrowing shrimp, we have identified the following five topics as the most critical areas in which additional research is needed. In our opinion, all five topics are fundamental to any rational approach to the control of burrowing shrimp on oyster beds, whether or not that approach is called IPM.

1. Development of Accurate Shrimp Population Census Methods: Accurate estimates of the population densities of ghost and mud shrimp are fundamental to all aspects of decision making in the burrowing shrimp IPM plan. The current practice of using burrow counts obtained in early spring provides very poor estimates of the true density of burrowing shrimp on the tide flat being inspected. Burrow counts collected between May and October provide better predictions of shrimp abundance, but have several drawbacks, including burrow-to-shrimp ratios that vary among locations, lack of information about the demography of the shrimp population (i.e., ages, sizes, sex ratio, reproductive condition), and lack of information about the relative abundance of each species. Sediment cores provide highly detailed measurements of the demographics and abundances of each species, but are impractical because of the labor required to collect and process each sample. New approaches should be developed that are accurate, rapid, and inexpensive (in that order of importance). Possibilities include side-scanning sonar, acoustical imaging, and a modification of the "boot method" used informally by oyster growers. The latter method, described in Chapter 4, would provide both an estimate to the shrimp population (albeit using burrow counts), as well as an estimate of their damage to oysters. A multi-site study should be conducted initially to compare data obtained from many habitats

(different sediment types, tidal elevations, salinity regimes, eelgrass densities) using the new method with data obtained from the sediment core sampling and burrow count methods. Long-term studies should be conducted to determine the utility of the data obtained from each sampling method.

2. Characterization of Damage/Density Function: Knowledge of the quantitative relationships between burrowing shrimp density and impacts to oyster production is fundamental to developing objective criteria for deciding when and where to initiate tactics to control burrowing shrimp. The mathematical formula that describes the relationship between the abundance of the pest and the reduction to the yield of the crop is known in IPM parlance as the damage/density function. Separate damage/density functions will exist for each species of pest, for each major cultural practice (i.e., bottom, longline, and rack and bag culture), and sometimes for different parts of the crop cycle (i.e., seed beds and fattening beds in bottom culture). Furthermore, damage/density functions might vary with habitat type (i.e., oysters might be more tolerant of burrowing shrimp on some sediments or tidal elevations than on others) and possibly with season (i.e., inactive shrimp in the winter might not exert as much damage as shrimp in the summer). There is insufficient information to characterize damage/density functions for any aspect of oyster culture. To generate damage/density functions, studies should be undertaken to measure the survival, growth, and harvest yield of oysters on beds with different densities of burrowing shrimp, in different habitats, and at different times of year. Studies should initially focus on developing damage/density functions for the cultural practices suffering the greatest economic loss from burrowing shrimp. If those efforts are successful, then additional field studies should be undertaken to develop damage/density functions for other aspects of oyster culture.

3. Development of Alternative Methods and Timing for Delivery of Carbaryl: The current practice of aerial spraying of carbaryl does not accurately deliver the pesticide to the burrowing shrimp; rather, it spreads it across the oyster bed, and only a small proportion of the chemical actually enters each burrow. Studies to evaluate more methods to more precisely deliver carbaryl to the burrows could dramatically reduce the amount of pesticide that is applied on each bed.

Possible technologies were discussed in Section 6.1.2, involving ground application. In addition, studies are needed to determine whether application of carbaryl at seasons other than mid-summer would be 1) effective at controlling shrimp, and 2) environmentally acceptable. Application of carbaryl in the Fall, shortly after recruitment of YOY ghost shrimp, could add at least on year to the frequency at which beds need to be sprayed. Evaluation of alternative methods to deliver carbaryl should include effectiveness at controlling shrimp, the economic benefits and costs, and the environmental benefits and costs.

4. Determination of Underlying Reasons for Increased Burrowing Shrimp Populations: Long-term reduction of the impact of burrowing shrimp on oysters will require knowledge of, and the ability to change, the factors that led to the expansion of burrowing shrimp populations in Willapa Bay and Grays Harbor. Growers and resident biologists report that burrowing shrimp populations have increased dramatically in Willapa Bay and Grays Harbor since the 1950s. Stories of historical increases in shrimp populations are also reported for Oregon estuaries. No studies have been conducted to determine why the populations have expanded or to search for documentation of when, where, or how fast the expansion occurred. Many hypotheses have been suggested, including El Niño climatic changes, sedimentation caused by upland land management, reductions in the abundance of shrimp predators, damming of the Columbia River and other rivers, changes in the salinity structure of the estuarine water column, or aquaculture activities. Based on reports of population expansion in neighboring states, it is plausible that the responsible process operates at a regional scale. Studies to determine the responsible practice should start by searching historical archives for physical evidence of changes in burrowing shrimp distributions and changes in environmental conditions within Willapa Bay, Grays Harbor, and other Pacific Northwest estuaries. Sediment cores and dating techniques may provide additional evidence of historical changes in patterns of burrowing shrimp bioturbation in different parts of the estuary. Oral histories of burrowing shrimp distributions and estuarine conditions should be constructed from interviews with oyster growers and local biologists. These three sources of information would help identify when the shrimp populations expanded and what environmental conditions might have accompanied (or precipitated) that event. Experiments

could then be conducted to measure the responses of burrowing shrimp to these environmental factors, from which the cause of population increase might be identified.

5. <u>Development of Objective Decision-Making Criteria for Use of Control Tactics</u>: The economic injury level (EIL) and economic threshold (ET) models underlie the formal decision-making process for IPM. We found that the basic EIL model used in terrestrial IPM plans was too simplistic to describe the interactions between burrowing shrimp and oyster culture. A fundamentally new EIL model should be developed that includes provision for the multi-year, multi-season crop production cycle, seasonal changes in the damage caused by the shrimp, and the effects of other environmental factors on the physiology and growth of oysters and shrimp. This EIL should build upon the damage/density model proposed in item 2 in this list, and the ET model should use the recommended census method (item 1).

8.4.2 Additional Information Needs in Burrowing Shrimp Ecology

- <u>Development of Burrowing Shrimp Population Models</u>: Population models for ghost and mud shrimp would provide oyster growers and other environmental managers with the ability to forecast the size of burrowing shrimp populations one or two years in the future. Coupled with the damage/density function, a population model becomes a tool for predicting the probability of future damage to the oyster crop. These coupled models would, in essence, be the heart of any future EIL or ET models. The data sets we evaluated were inadequate to develop a population model for either species of shrimp. Clearly, separate models will be required for ghost and mud shrimp. A prerequisite for constructing a population model is an accurate method of censussing population size, and the population model should be built so that data from routine shrimp censuses could be directly added to the population model database. We recommend that efforts be directed toward development of stage-matrix demographic models that can be used to forecast future population densities of shrimp on individual oyster beds, given site-specific information about the existing populations and rates of recruitment.

- Recruitment and Colonization by Burrowing Shrimp: The rates at which ghost and mud shrimp invade sediments, either as larvae or via above-ground movements of 1+ and older shrimp, need to be measured. The temporal and spatial components of colonization within the estuaries and whether migration is density-dependent or varies with gender or age class, also needs to be determined. In addition, the spatial component of larval transport within the estuaries (i.e., does differential larval transport contribute to shrimp population regulation and variation among sites or with respect to shrimp density?), as well as habitat preferences of larvae of ghost and mud shrimp, needs to be examined. Methods are also needed to routinely monitor rates of shrimp recruitment onto individual oyster beds, which would help growers predict the abundance of shrimp in the following year. Information will support development of population models and may provide suggestions for methods of inhibiting the success of recruitment or colonization.

- Estimation of Mortality Rates: For each species of burrowing shrimp, the biotic and abiotic factors that influence natural mortality (e.g., conspecific density, environmental conditions, disturbance, predation risk) need to be quantified.

- Identification and Ecology of Predators of Burrowing Shrimp: The importance of the major predators of ghost and mud shrimp (larvae, YOY, and 1+ adults), the habitat and environmental requirements of the most important (quantitatively) predators, and methods of augmenting predator populations on or near oyster beds as a method of biological control, need to be identified.

- Competition Between Burrowing Shrimp: The intra- and interspecific interactions between ghost shrimp and mud shrimp that can influence population density and species composition on oyster beds need to be more fully examined.

8.4.3 Additional Information Needs for Cultural Practices

- Integrate Eelgrass into Oyster Farming: Methods need to be developed that promote the growth of eelgrass on or immediately adjacent to oyster beds to provide predators of burrowing shrimp with refuge habitat. Possibilities include use of machinery or practices that are more compatible with eelgrass growth and alternate-strip planting of eelgrass and oyster beds. Providing refuge habitat for the predators could lead to slower population growth rates for shrimp on the oyster beds. Other practices that control burrowing shrimp populations (such as pesticides) may help to promote growth of eelgrass.

- New Markets for Burrowing Shrimp: Markets could be developed for the shrimp as seafood items or components in seafood products. Potential customers include Asian and ethnic diners. Products need not be limited to food items; investigations should be made to determine whether burrowing shrimp have value for medicinal or pharmaceutical products.

- Shrimp-Tolerant Crops: Other crops should be sought that could be grown using rack culture methods for which loss of the crop from the racks is minimal. Recent research demonstrates that Manila clams can be grown in cages within mud shrimp habitat. Other possibilities include other bivalves or seaweeds.

8.4.4 Additional Information Needs for Control Practices

- Enhance Habitat for Predators: Similar to the call to increase eelgrass on oyster beds, growers should enhance on beds the habitat features that will attract shrimp predators to their oyster beds (i.e., staghorn sculpin, white sturgeon, cutthroat trout). This could include providing structures that allow predators more time to forage for burrowing shrimp (i.e., using dikes and dams to create ponds on oyster beds), offer refuge from predation, or that encourage mating (i.e., cover, crevices, vegetation). Literature reviews should be conducted to summarize current knowledge about the estuarine habitat requirements of these predators, followed by field studies to test whether manipulation of these habitat elements increases the densities of predators and reduces burrowing shrimp population density.

- Physical Control of Shrimp Recruits: Newly recruited shrimp (especially ghost shrimp) might be more susceptible to disturbance of the sediment surface than are adults. Physical control methods that might be effective include sediment compaction and harrowing. Local enhancement of predators could increase the effectiveness of this method by encouraging predators to forage on shrimp forced to the surface by the physical control. Application of physical controls during periods of very low salinity might expose young shrimp to lethal conditions (osmotic shock).

- Integrating Control Methods: The integration of chemical, biological, and physical control methods needs to be further studied. Some suggestions are listed in Chapter 6.

- Development of Other pesticides: New generation pesticides that have higher toxicological specificity to arthropods should be investigated for use to control burrowing shrimp. Progress on initial research is discussed in Chapter 6. Research should be conducted to address concerns about impacts of new pesticides to environmental and human resources identified by growers and other experts (Chapter 6).

8.4.5 Additional Information Needs for Decision Criteria and Thresholds

- Economic Data for Oyster Beds: In order to better characterize the economic impacts of burrowing shrimp, oyster growers should keep careful records of the farming costs and yields on each of their oyster beds, as well as annual changes in the abundance of burrowing shrimp on each bed. Growers should track the density of oysters planted on the bed (as seed or juvenile oysters), the labor effort to manage the bed, the yield of oysters (as both bushels of oysters and gallons of meat) per acre, and the density and species of burrowing shrimp occupying the beds. Much of these data are likely to be proprietary, and should be made available to researchers only if assurances are made that the business interests of the growers will be protected.

- Environmental Costs and Benefits: In order to make sound decisions within an IPM framework, a better understanding is needed of the total costs and benefits (both economic and environmental) of alternative control practices (whether the alternatives include different rates and methods of pesticide application or other control methods). Estimation of environmental costs and benefits is a complex task given the wide range of ecosystem functions and services that may be impacted and limitations to the existing methods to assess the monetary value of nonmarket and especially non-use services provided by ecosystems.

- Sampling Plan: After the development of an accurate shrimp population census method, and after EIL and ET models are developed, a new sampling plan must be developed using the approach described in Chapter 8.

8.5 IMPLEMENTATION OF AN IPM PLAN

In order to move the ideas and tools described in this report from theory into practice, we provide the following suggestions that oyster growers and resource agencies will need to implement any IPM plan that is ultimately developed.

8.5.1 Communication of the IPM Plan. In order for the growers and resource agencies to evaluate and implement an IPM plan, they must know of its existence, be able to review it, and have opportunities to discuss the suggestions contained in this report. Thus, the first step toward implementing this plan is to distribute this report as widely as possible. The report should be printed in a durable format and published under the auspices of a credible scientific or natural resources organization, such as the American Fisheries Society. Publication costs should be shared by the beneficiaries of the IPM plan (i.e., resource agencies and oyster growers). The second step should be to hold public meetings at which the authors of this study and members of the Burrowing Shrimp Control Committee are present to review the IPM plan and to discuss the suggestions with the audience.

8.5.2 IPM Plan Coordinator. A process should be established to monitor the implementation of the IPM plan, to incorporate new developments within the IPM plan, and to identify and prioritize needs for new information. One such process would be to have the Burrowing Shrimp Control Committee (BSCC) identify an individual whose responsibility is to maintain the IPM plan, to convene meetings of the BSCC or other groups as needed to discuss developments in the IPM plan, direct the IPM research strategy, keep abreast of research on IPM-related topics, and to prepare an annual report on the status of the IPM plan. This effort would require at least 20% of this individual's time annually (probably more in the first year), and adequate resources should be provided to compensate this level of effort.

8.5.3 A State-Owned and Grower-Operated Demonstration Farm. Many of the control techniques and cultural practices suggested in Chapter 6 are new to oyster growers or have not been evaluated rigorously for their efficacy at controlling burrowing shrimp, costs, or impacts to the environment. Given the economic and environmental uncertainties associated with some of these practices and the benefits that might derive from successful studies, oyster growers and resource agencies should develop a partnership to test and refine shrimp control methods, sharing the risks and benefits associated with the development efforts. A centerpiece for such a partnership could be a demonstration farm, set up on state-owned oyster lands, farmed by oyster growers, and managed cooperatively by WDFW shellfisheries biologists and oyster growers. As implied by the name, the purpose of the farm would be to test control and culture methods in a setting that minimizes economic risk to the growers (their losses would be limited to labor and materials used to grow the oysters and deploy the control tactics) and maximizes long-term benefits to the state's interests (i.e., increasing benefits to natural resources and economic development in the region). Management of the culture and control operation should be shared cooperatively between the growers and the state, and must be conducted in a scientifically rigorous manner.

8.5.4 Improvement of Relationships Among Stakeholders. Trust, respect, and cooperation among stakeholders will strongly influence the implementation and success of this IPM plan. Although most aspects of terrestrial agriculture IPM plans are not closely regulated, control of burrowing shrimp in oyster beds in estuaries has attracted the concerns of state and federal resource agencies, tribes, citizens' groups, and oyster growers. Lack of trust, stubbornness, unwillingness to participate in constructive dialog, changing environmental values, and lack of information have contributed to discord surrounding burrowing shrimp control practices (Eng 1995). One step toward reducing conflict among stakeholders would be to increase education of staff in resource agencies, the public, and oyster growers as to the true benefits (economic and environmental) and costs (environmental) of burrowing shrimp control. Another step would be to continue forums to openly discuss burrowing shrimp control practices, such as those conducted by the BSCC, which includes representatives of resource agencies, oyster farmers, academic scientists, tribes, and citizens' groups.

8.5.5 Improved Respect for "Local" Knowledge. Many of our respondents felt that information that they provide to decision makers at the State level is not seriously considered when decisions are made about pesticide applications, etc. For example, many feel that decisions as to timing of application are not based on good science. Staff in resource agencies and scientists in research institutions should learn to have greater respect the experience of oyster growers and local naturalists who live and work on the estuaries. In addition, oyster growers and local naturalists need to maintain written and photographic records and to take quantitative measurements of environmental variables and processes in order to better substantiate the validity of their observations and conclusions.

8.5.6 Resources to Implement the IPM Plan. In order to implement the IPM plan and conduct research to address critical research needs, the State and the oyster growers will need knowledge and financial resources. Institutions that have expertise that could assist these efforts include state resource agencies (WDFW, WDOE, WDNR, Washington Sea Grant), federal resource agencies (USFW, USEPA, USACE, NMFS, USGS), private-sector research institutions and consultants (such as Battelle, Aquatic Environmental Services), academic institutions (University of Washington, Western Washington University, Oregon State University, Grays Harbor College, Peninsula College, Washington State University), and non-government organizations and foundations (Willapa Alliance, Olympic Natural Resources Center, Eco-Trust). Financial resources could be contracts or grants from private and commercial sources (oyster growers, seafood distributers, venture capitalists), state agencies (WDOE, WDFW, WDNR, WDA, Washington Sea Grant, Washington State Commission on Pesticide Registration), and federal agencies (USEPA, USFW, NCRI, USDA, and possibly NSF). Cooperative-funding partnerships between commercial, state, and federal organizations are likely to be especially productive, given current tight budgets .

8.6 FURTHER DEVELOPMENT OF THE IPM PLAN

The IPM plan must have the capacity and capability to change and improve over time. In particular, as the critical information needs are addressed (Section 9.2.1), improvements will be more accurate methods of censussing shrimp populations, models of forecasting changes in shrimp population size, objective criteria for deciding when and where to apply control tactics, and insights to factors causing burrowing shrimp populations to expand in recent decades. Additional improvements are foreseen in burrowing shrimp control methods, with the conservation and enhancement of natural populations of shrimp predators, and with studies to integrate existing control practices. As suggested in Section 9.3.2, a coordinator could be responsible for tracking the research and upgrading the IPM plan. An oversight committee (such as the BSCC) should review progress and implementation of the IPM plan on biennial basis and provide guidance to the IPM coordinator as to how efforts should be prioritized. By regularly incorporating new knowledge into the plan, and by regularly disseminating improvements to the plan, the oyster growers and resource agencies will see steady progress toward the IPM plan's goal of maximizing profit from the production of oysters while minimizing deleterious impacts to other environmental or human resources.

9.0 LITERATURE CITED

Allanson, B.R., D. Skinner, and J. Imberger. 1992. Flow in prawn burrows. Estuar. Coast. Shelf Sci. 35:253-266.

Aller, R.C., and R.E. Dodge. 1974. Animal-sediment relations in a tropical lagoon Discovery Bay, Jamaica. J. Mar. Res. 32:209-232.

Angell, C.L. 1986. The Biology and Culture of Tropical Oysters. ICLARM Studies and Reviews Vol. 13, International Centre for Living Aquatic Resources Management, Manila, Philippines.

Anima, R.J., H.E. Clifton, and R.L. Phillips. 1989. Comparison of modern and pleistocene estuarine facies in Willapa Bay, Washington. *In* G.E. Reinson, ed., "Modern and Ancient Examples of Clastic Tidal Deposits - A Core and Peel Workshop", Canadian Society of Petroleum Geologists, Calgary, Alberta, Canada.

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

Armstrong, D.A., O. Iribarne, P.A. Dinnel, K.A. McGraw, J.A. Shaffer, R. Palacios, M. Fernandez, K. Feldman, and G. Williams. 1992. Mitigation of Dungeness crab, *Cancer magister*, losses due to dredging in Grays Harbor by development of intertidal shell habitat: pilot studies during 1991. FRI-UW-9205. University of Washington, Seattle, WA.

Armstrong, D. A., K.A. McGraw, P.A. Dinnel, R.M. Thom, and O. Iribarne. 1991. Construction dredging impacts on Dungeness crab, *Cancer magister*, in Grays Harbor, Washington and mitigation of losses by development of intertidal shell habitat. FRI-UW-9110. University of Washington, Seattle, WA.

Armstrong, D.A., and R.E. Millemann. 1974a. Effects of the insecticide carbaryl on clams and some other intertidal mud flat animals. J. Fish. Res. Bd. Can. 31:466-470.

Armstrong, D.A., and R.E. Millemann. 1974b. Pathology of acute poisoning with the insecticide Sevin on the bentnose clam, *Macoma nasuta*. J. Invert. Path. 24:201-212.

Armstrong, D.A., and R.E. Millemann. 1974c. Effects of the insecticide Sevin and its first hydrolytic product, 1-napthol, on some early developmental stages of the bay mussel *Mytilus edulis*. Mar. Biol. 28:11-15.

Bakalian, A.B. 1985. The use of sevin on estuarine oyster beds in Tillamook, Oregon. *Coastal Zone Management Journal* 13(1): 49-83.

Barnes, Robert D. 1980. Invertebrate Zoology. W.B. Saunders Co.. Philadelphia, Pennsylvania.

Bechinski, E.J. et al. 1989. Development of action thresholds for the sugarbeet root maggot (*Diptera Otitidae*). Journal of Economic Entomology 82(2):608-615.

Bird, E.M. 1982. Population dynamics of thalassinidean shrimps and community effects through sediment modification. Ph.D. Dissertation, University of Maryland, College Park.

Black, R., and C.H. Peterson. 1988. Absence of preemption and interference competition for space between large suspension-feeding bivalves and smaller infaunal macroinvertebrates. J. Exp. Mar. Biol. Ecol. 120:183-198.

Branch, G. M., and A. Pringle. 1987. The impact of the sand prawn *Callianassa kraussi* Stebbing on sediment turnover and on bacteria, meiofauna, and benthic microflora. J. Exp. Mar. Biol. 107:219-235.

Breese, W.P., and F.D. Phibbs. 1972. Ingestion of bivalve molluscan larvae by the polychaete annelid *Polydora ligni.* Veliger 4:274.

Brenchley, G. A. 1981. Disturbance and community structure: an experimental study of bioturbation in marine soft-sediment environments. J. Mar. Res. 39:767-790.

Brenchley, G. A. 1982. Mechanisms of spatial competition in marine soft-bottom communities. J. Exp. Mar. Biol. Ecol. 60:17-33.

Brooks, K. M. 1993. Changes in arthropod and mollusk populations associated with the application of Sevin to control burrowing shrimp in Willapa Bay, July to September, 1992. Report to the Pacific County Economic Development Council. 30 pp.

Brooks, K.M. 1995. Long-term response of benthic invertebrate communities associated with the application of carbaryl (Sevin) to control burrowing shrimp, and an assessment of the habitat value of cultivated Pacific oyster (*Crassostrea gigas*) beds in Willapa Bay, Washington, to fulfill requirements of the EPA carbaryl data call in. Final Report. Aquatic Environmental Services, Port Townsend, Washington.

Brooks, K.M. 1996-1997. Personal Communication. Aquatic Environmental Services, Port Townsend, Washington.

Brown, J.R., and W.G. Roland. 1987. Siting culture operations for the Pacific oyster *Crassostrea gigas*. Fisheries Development Report No. 34. Canadian Ministry of Agriculture and Fisheries, Victoria, British Columbia.

Buchanan, D.V., D.L. Bottom, and D.A. Armstrong. 1985. The controversial use of the insecticide Sevin in Pacific Northwest estuaries: its effects on Dungeness crab, Pacific oyster, and other species. Proceedings of the symposium on Dungeness crab biology and management. Alaska Sea Grant Rept. 85-3. University of Alaska, Fairbanks, p 401-417.

Burrowing Shrimp Control Committee (BSCC). 1992. Findings and recommendations and an integrated pest management plan for the control of burrowing shrimp on commercial oyster beds in Willapa Bay and Grays Harbor, Washington State. Report prepared for

Grays Harbor Board of County Commissioners, Pacific County Board of Commissioners, and Directors of Washington Department of Fisheries, Washington Department of Agriculture, and Washington Department of Ecology.

Carkner, R., and S. Harbell. 1992. Economic assessment of bottom versus off bottom oyster culture in Grays Harbor and Willapa Bay, Washington. Final Report. Washington State Cooperative Extension Agency, Washington State University, Puyallup, Washington.

Caswell, H. 1989. Matrix Population Models. Sinauer Associates. Sunderland, MA.

Clifton, H.E. 1980. Questions on coastal processes: contest or co-existence. *In* D.S. Simonett, ed., "Marine Sciences and Ocean Policy: a Definition of the Issues and a Concensus on Multiple Uses. University of California, Santa Barbara.

Clifton, H.E. 1983. Discrimination between subtidal and intertidal facies in Pleistocene deposits, Willapa Bay, Washington. J. Sedimentol. Petrol. 53: 353-369.

Clifton, H.E., and R.L. Phillips. 1980. Lateral trends and vertical sequences in estuarine sediments, Willapa Bay, Washington. *In* M.E. Field et al., eds., "Quartenary Depositional Environments of the Pacific Coast," Pacific Coast Paleogeographic Symposium 4, Soc. Econ. Palenotologists Mineralogists Pacific Section, p. 55-71.

Coleman, N., and G.C. Poore. 1980. The distribution of *Callianassa* species (Crustacea: Decapoda) in Western Port Victoria, Australia. Proc. R. Soc. Victoria 91:73-78.

Cole-Warner, L. 1997. U.S. Army Corps of Engineers, Seattle, Washington.

Commito, J.A., and E.M. Boncavage. 1989. Suspension-feeders and coexisting infauna: an enhancement counterexample. J. Exp. Mar. Biol. Ecol. 125:33-42.

Conway, R.S. 1991. The economic impact of the oyster industry. Final Report for Willapa-Grays Harbor Oyster Growers' Association, Washington State Department of Community Development, Pacific County Economic Development Council, and Port of Peninsula. Dick Conway and Associates, Seattle, Washington.

Darling, J. D. 1984. Gray whales off Vancouver Island, British Columbia. *In* Jones, M. L., Swartz, S. L., Leatherwod, S. (eds). The gray whale. Academic Press, Orlando, Florida.

Davis, R.M., M.D. Skold, J.S. Berry, and W.P. Kemp. 1992. The economic threshold for grasshopper control on public rangelands. Journal of Agricultural and Resource Economics 17(1):56-65.

Devine, C.E. 1966. Ecology of *Callianassa filholi* Milne-Edwards 1878 (Crustacea, Thalassinidea). Trans. Roy. Soc. N.Z. Zool. 8:93-110.

Dittmann, S. 1996. Effects of macrobenthic burrows on infaunal communities in tropical tidal flats. Mar. Ecol. Prog. Ser. 134:119-130.

Doty, D.C., D.A. Armstrong, and B.R. Dumbauld. 1990. Comparison of carbaryl pesticide impacts on Dungeness crab (*Cancer magister*) versus benefits of habitat derived from oyster culture in Willapa Bay, Washington. Report to the Willapa Bay/ Grays Harbor Oystergrowers Association. 69 pp.

Dumbauld, B.R.. 1995-1997. Personal Communication. Washington Department of Fisheries and Wildlife, Nahcotta, Washington.

Dumbauld, B.R. 1994. Thalassinid shrimp ecology and the use of carbaryl to control populations on oyster ground in Washington coastal estuaries. Ph.D. Dissertation, University of Washington, Seattle.

Dumbauld, B.R., D.A. Armstrong, and T.L. McDonald. 1993. Use of oyster shell to enhance intertidal habitat and mitigate loss of Dungeness crab (*Cancer magister*) caused by dredging. Can. J. Fish. Aquat. Sci. 50:381-390.

Dumbauld, B.R., D.A. Armstrong, and K.L. Feldman. 1996. Life-history characteristics of two sympatric thalassinidean shrimps, *Neotrypaea californiensis* and *Upogebia pugettensis* with implications for oyster culture. J. Crust. Biol. 16:689-708.

Dumbauld, B.R. et al. 1997. Ghost shrimp control and eelgrass (*Zostera japonica*) distribution. Abstract, Pacific Estuarine Research Society Annual Meeting, Tillamook, Oregon.

Durfey, J. 1996. Personal Communication. Department of Biosystems Engineering, Washington State University, Pullman, Washington.

Dworschak, P. C. 1987. The biology of *Upogebia pusilla* (Petagna) (Decapoda, Thalassinidea) II. Environments and zonation. Mar. Ecol. 8:337-358.

Dworschak, P. C. 1988. The biology of *Upogebia pusilla* (Petagna) (Decapoda, Thalassinidea) III. Growth and production. Mar. Ecol. 9:51-77.

Ebbesmeyer, C.C., and R.M. Strickland. 1995. Oyster condition and climate: evidence from Willapa Bay. Report to Washington Sea Grant for the 5th Conference for Shellfish Growers, Olympia, Washington. WS6-MR95-02.

Eckman, J. E. 1983. Hydrodynamic processes affecting benthic recruitment. Limnol. Oceanogr. 28:241-257.

Eckman, J. E. 1985. Flow disruption by an animal-tube mimic affects sediment bacterial colonization. J. Mar. Res. 43:419-435.

Eckman, J.E., A.R.M. Nowell, and P.A. Jumars. 1981. Sediment destabilization by animal tubes. J. Mar. Res. 39:361-374.

Else, P.V. 1987. Oyster culturing methods. *In*: P.V. Else, B. Paust, and D.M. Burns. Alaska Oyster Grower's Manual. 3rd Edition. Alaska State Department of Commerce and Economic Development, Office of Commercial Fisheries Development. Juneau, Alaska.

Eng, M. 1995. The burrowing shrimp control committee: a failed opportunity for collaboration. Masters thesis, University of Washington, Seattle, Washington. 140 p.

Engvall, B. 1995-1997. Personal Communication. Brady's Oysters, Grayland, WA.

Felder, D.L., and D.L. Lovett. 1989. Relative growth and sexual maturation in the estuarine ghost shrimp *Callianassa louisanenesis*. J. Crust. Biol. 9:529-539.

Feldman, K.L., D.A. Armstrong, D.E. Eggleston, and B.R. Dumbauld. *In press*. Effects of substrate selection and post-settlement survival on recruitment success of the thalassinidean shrimp, *Neotrypaea californiensis*, to intertidal shell and mud habitats. Mar. Ecol. Prog. Ser.

Feldman, K.L. 1995-1997. Personal Communication. School of Fisheries, University of Washington, Seatte, WA

Flint, M.L. and R. van den Bosch. 1981. Introduction to Integrated Pest Management. Plenum Press, NY.

Greer, Glen and R.L. Sheppard. 1990. An Economic evaluation of the benefits of research into biological control of *Clematis Vitalba*. Research Report No. 203. Agribusiness & Economics Research Unit. Lincoln College, Canterbury, New Zealand.

Griffis, R.B. 1988. Behavioral interactions between burrowing shrimp: effects on distribution of sympatric thalassinids. Am. Zool. 28:179A.

Griffis, R.B., and F.L. Chavez. 1988. Effects of sediment type on *Callianassa californiensis* Dana and *C. gigas* Dana. J. Exp. Mar. Biol. Ecol. 117:239-253.

Griffis, R.B., and T.H. Suchanek. 1991. A model of burrow architecture and trophic modes in thalassinidean shrimp (Decapoda: Thalassinidea). Mar. Ecol. Prog. Ser. 79:171-183.

Grundy, T.P. 1989. An economic evaluation of biological control of sweet brier. Research Report No. 201. Agribusiness & Economics Research Unit. Lincoln College, Canterbury, New Zealand.

Grundy, T.P. 1989. An economic evaluation of biological control of *Hieracium*. Research Report No. 202. Agribusiness & Economics Research Unit. Lincoln College, Canterbury, New Zealand.

Hailstone, T.S., and W. Stephenson. 1961. The biology of *Callianassa* (*Trypaea*) *australiensis* Dana 1852 (Crustacea, Thalassinidea). Univ. of Queensland Dept. Zool. Papers 1:257-286.

Hall, D.C. and R.B. Norgaard. 1973. On the timing and application of pesticides. American Journal of Agricultural Economics. 55: 198-201.

Hanekom, N., and T. Erasmus. 1988. Variations in size compositions of populations of *Upogebia africana* (Ortmann) (Decapoda, Crustacea) within the Swartkops estuary and possible influencing factors. S. Afr. J. Zool. 23:259-265.

Harper, J.K., J.W. Mjelde, M.E. Rister, M.O. Way and B.M. Drees. 1994. Developing flexible economic thresholds for pest management using dynamic programming. Journal of Agriculture and Applied Economics. 26(1):134-147.

Harrison, P.G. 1987. Natural expansion and experimental manipulation of seagrass (*Zostera* spp.) abundance and the response of infaunal invertebrates. Estuar. Coast. Shelf Sci. 24:799-812.

Hart, J. L. 1937. Larval and adult stages of British Columbia anomura. Can. J. Res. 15:179-220.

Hart, J. L. 1974. Pacific fishes of Canada. Fish. Res. Board Can., Bull. 180, 740 pp.

Headley, J.C. 1972. Defining the economic threshold. *In:* Pest Control Strategies for the Future. National Academy of Sciences, Washington, D.C. pp. 100-108.

Highsmith, R. C. 1982. Induced settlement and metamorphosis of sand dollar *(Dendraster excentricus*) larvae in predator-free sites: adult sand dollar beds. Ecology 63: 329-337.

Higley, L.G. and W.K. Wintersteen. 1992. A novel approach to environmental risk assessment of pesticides as a basis for incorporating environmental costs into economic injury levels. American Entomologist, Spring: 34-39.

Higley, L.G. 1996-1997. Personal Communication. University of Nebraska, Lincoln, NB.

Hill, B. J. 1981. Respiratory adaptations of three species of Upogebia (Thalassinidea, Crustacea) with special reference to low tide periods. Biol. Bull. 160:272-279.

Hill, Richard L. 1986. Biological control of gorse: implications for the natural environment and for primary production. Entomology Division Report No. 6. DSIR, Private Bag, Christchurch.

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

Iribarne, O., D. Armstrong, and M. Fernandez. 1995. Environmental impact of intertidal juvenile dungeness crab habitat enhancement: effects of bivalves and crab foraging rate. J. Exp. Mar. Biol. Ecol. 192: 173-194.

James, B. 1996-1997. Washington Department of Fish and Wildlife, Battle Ground, Wa.

John, K.H., J.R. Stoll and J.K. Olson. 1987. An economic assessment of the benefits of mosquito abatement in an organized mosquito control district. Journal of American Mosquito Control Association. 3(1):8-14.

Johnson, G.E., and J.J. Gonor. 1982. The tidal exchange of *Callianassa californiensis* (Crustacea, Decapoda) larvae between the ocean and Salmon River estuary, Oregon. Estuar. Coast. Shelf Sci. 14:501-516.

Johnston, R.L. and G.W. Bishop. 1987. Economic injury levels and economic thresholds for cereal aphids (homoptera: Aphidisae) on spring-planted wheat. Journal of Economic Entomology 80(2): 478-482.

Jumars, P.A., and A.R.M. Nowell. 1984. Effects of benthos on sediment transport: difficulties with functional grouping. Cont. Shelf Res. 3:115-130.

Kalinowski, S.A., R.C. Martin, and L.D. Cooper. 1982. Wildlife studies on proposed disposal sites in Grays Harbor, Washington. Grays Harbor and Chehalis River Improvements to Navigation Environmental Studies. Report for Contract DACW67-80-C-0091. Seattle District of the U.S. Army Corps of Engineers, Seattle, Washington.

Kincaid, T. 1968. The ecology of Willapa Bay, Washington, in relation to the oyster industry. Unpublished manuscript. Seattle, WA.

King, S. 1996-1997. Personal Communication. Oregon Department of Fish and Wildlife, Portland, OR.

Koike, I., and H. Mukai. 1983. Oxygen and inorganic nitrogen contents and fluxes in burrows of the shrimps *Callianassa japonica* and *Upogebia major.* Mar. Ecol. Prog. Ser. 12:185-190.

Lebovitz, A. 1996. Personal Communication. Willapa Alliance, South Bend, WA.

Leistritz, F.L., F. Thompson, and J. A. Leitch. 1992. Economic impact of leafy spurge *(Euphoria esula)* in North Dakota. Weed Science 40:275-280.

Loehr, L.C., and E.E. Collias. 1981. A review of water characteristics of Grays Harbor 1938-1979 and an evaluation of possible effects of the proposed channel widening and deepening project upon present water characteristics. Final Report for Contract DACW67-80-C-0009. Grays Harbor and Chehalis River Improvements to Navigation Environmental Studies. Seattle District of the U.S. Army Corps of Engineers, Seattle, Washington.

Loosanoff, V.L., and F.D. Tommers. 1948. Effect of suspended silt and other substances on rate of feeding of oysters. Science 107:69-70.

Luckenbach, M.W. 1984. Settlement and early post-settlement survival in the recruitment of *Mulinia lateralis* (Bivalvia). Mar. Ecol. Prog. Ser. 17:245-250.

MacDonald, P. D. M., and T.J. Pitcher. 1979. Age-groups from size-frequency data: a versatile and efficient method of analyzing distribution mixtures. J. Fish. Res. Bd. Canada 36:987-1001.

MacGinitie, G. E. 1930. The natural history of the mud shrimp *Upogebia pugettensis* (Dana). Ann. Mag. Nat. Hist. 6:37-45.

MacGinitie, G. E. 1934. The natural history of *Callianassa californiensis* (Dana). Am. Midl. Nat. 15:166-177.

Magoon, C. and R. Vining. 1981. Introduction to shellfish aquaculture in the Puget Sound region. Washington Dept. of Natural Resources, Div. Marine Land Management, Olympia, WA.

Manning, R.B., and D.L. Felder. 1991. Revision of the American Callianassidae (Crustacea: Decapoda: Thalassinidea). Proc. Biol. Soc. Washington 104: 764-792.

Mauer, D. 1983. The effect of an infaunal suspension feeding bivalve *Mercenaria mercenaria* (L.) on benthic recruitment. P.S.Z.N.I. Mar. Ecol. 4:263-274.

McConnaughey, R. A., D.A. Armstrong, B.M. Hickey, and D.R. Gunderson. 1992. Juvenile Dungeness crab (*Cancer magister*) recruitment variability and oceanic transport during the pelagic larval phase. Can. J. Fish. Aquat. Sci. 49:2028-2044.

McCrow, L. T. 1972. The ghost shrimp, *Callianassa californiensis* Dana, 1854, in Yaquina Bay, Oregon. M.Sc. thesis, Oregon State University, Corvallis.

Miller, M. F. 1984. Bioturbation of intertidal quartz-rich sands: a modern example and its sedimentologic and paleoecologic implications. J. Geol. 92:201-216.

Moffat, A.S. 1993. New Chemicals Seek to Outwit Insect Pests. Science, vol. 261.

Mukai, H., and I. Koike. 1984. Behavior and respiration of the burrowing shrimps *Upogebia major* (De Haan) and *Callianassa japonica* (De Haan). J. Crust. Biol. 4:191-200.

Mumford, J.D. and G.A. Norton. 1984. Economics of decision making in pest management. Annual Review of Entomology. 29: 157-174.

Murphy, R.C. 1985. Factors affecting the distribution of the introduced bivalve, *Mercenaria mercenaria*, in a California lagoon--the importance of bioturbation. J. Mar. Res. 43:673-692.

Nickell, L.A., and R.J.A. Atkinson. 1995. Functional morphology of burrows and trophic modes of three thalassinidean shrimp species, and a new approach to the classification of thalassinidean burrow morphology. Mar. Ecol. Prog. Ser. 128:181-197.

Nosho, T. 1989. Small-scale oyster farming for pleasure and profit. Washington Sea Grant-Aquaculture Series 89-1, Marine Advisory Services, Seattle, WA.

Onstad, D.W. 1987. Calculation of economic-injury levels and economic thresholds for pest management. Journal of Economic Entomology 80(2):297-303.

Oregon Department of Fish and Wildlife. 1977. Identification, distribution, and notes on food habits of fish and shellfish in Tillamook Bay, Oregon. Federal Aid Progress Report.

Pedigo, L.P. 1989. Entomology and Pest Management. Macmillan, New York.

Pedigo, L.P., L.G. Higley and P.M. Davis. 1989. Concepts and advances in economic thresholds for soybean entomology. World Soybean Research Conference, 3: 1487-1493.

Pedigo, L.P and L.G. Higley. 1992. The economic injury level concept and environmental quality.: a new perspective. American Entomologist, Spring: 12-21.

Peterson, C.H. 1977. Competitive organization of the soft-bottom macrobenthic communities of Southern California lagoons. Mar. Biol. 43:343-359.

Pimentel, G.E. 1983. Recruitment of larvae of the ghost shrimp, *Callianassa californiensis* (Crustacea, Decapoda) in the South Slough estuary, Oregon. M.Sc. thesis, Oregon State University, Corvallis.

Posey, M. H. 1985. The effects upon the macrofaunal community of a dominant burrowing deposit feeder, *Callianassa californiensis*, and the role of predation in determining its intertidal distribution. Ph.D. Dissertation, University of Oregon, Eugene.

Posey, M. H. 1986a. Changes in a benthic community associated with dense beds of a burrowing deposit feeder, *Callianassa californiensis*. Mar. Ecol. Prog. Ser. 31:15-22.

Posey, M. H. 1986b. Predation on a burrowing shrimp: distribution and community consequences. J. Exp. Mar. Biol. Ecol. 103:143-161.

Posey, M. H. 1987a. Effects of lowered salinity on activity of the ghost shrimp *Callianassa californiensis*. Northwest Sci. 61:93-96.

Posey, M. H. 1987b. Influence of relative mobilities on the composition of benthic communities. Mar. Ecol. Prog. Ser. 39:99-104.

Posey, M. H. 1990. Functional approaches to soft-substrate communities: how useful are they? Rev. Aquat. Sci. 2:343-356.

Posey, M.H., B.R. Dumbauld, and D.A. Armstrong. 1991. Effects of a burrowing mud shrimp, *Upogebia pugettensis* (Dana), on abundances of macro-infauna. J. Exp. Mar. Biol. Ecol. 148:283-294.

Quayle, D.B. 1988. Pacific oyster culture in British Columbia. Canadian Bulletin of Fisheries and Aquatic Sciences 218, Ottawa, Canada.

Radtke, H. 1993. An economic evaluation of biological control of tansy ragwort. Oregon Department of Agriculture State Weed Board.

Raupp, M.J., J.A. Davidson, C.S. Koehler, C.S. Sadot, and K. Reichelderfer. 1987. Bulletin of the Entomology Society of America 34:27-32.

Reiling, S.O., K.J. Boyle, M.L. Phillips, V.A. Trefts, and M.W. Anderson. 1988. The Economic benefits of late season black fly control. Maine Agricultural Experiment Station Technical Bulletin 822.

Regev, U., A.D. Gutierrez, and G. Feder. 1976. Pests as a common property resource: a case study of alfalfa weevil control. American Journal of Agricultural Economics 58:186-199.

Rhoads, D.C., and D.K. Young. 1970. The influence of deposit feeding organisms on sediment stability and community trophic structure. J. Mar. Res. 28:150-178.

Rice, D.W., and A.A. Wolman. 1971. The life history and ecology of the gray whale (*Eschrichtius robustus*). Am. Soc. Mamm., Spec. Publ. 3, 142 pp.

Richter, P.O. 1966. Biological control of insects and weeds in Oregon. Technical Bulletin No. 90. Agricultural Experiment Station, Oregon State University, Corvallis, Oregon.

Ringold, P. 1979. Burrowing, root mat density, and the distribution of fiddler crabs in the eastern United States. J. Exp. Mar. Biol. Ecol. 36:11-21.

Ronan, T.E. 1975. Structural and paleo-ecological aspects of a modern marine soft-sediment community: an experimental field study. Ph.D. Dissertation, University of California, Davis.

Rowden, A.A., and M.B. Jones. 1993. Critical evaluation of sediment turnover estimates for Callianassidae (Decapoda: Thalassinidea). J. Exp. Mar. Biol. Ecol. 173:265-272.

Rudy, P., and L. Rudy. 1983. Oregon Esturarine Invertebrates: An Illustrated Guide to the Common and Important Invertebrate Animals. Contract Nol 79-111. U.S. Fish and Wildlife Service. Portland, Oregon.

Ruesink, W.G. and M. Kogan, 1975. The quantitative basis for pest management: sampling and measuring. pp. 309-351. *In:* R. L. Metcalfand W. H. Luckman (eds.), Introduction to Insect Pest Management. Wiley, New York.

Russo, R. A. 1975. Observations on the food habits of leopard sharks (*Triakis semifasciata*) and brown smooth-hounds (*Mustelus henlei*). Cal. Fish. Game. 61:95-103.

Sayce, C. 1995-1997. Personal Communication. South Bend, WA.

Senanyake, D.G. and N.J. Holliday. 1990. Economic injury levels for colorado potato beetle *(Coleoptera: Chrysomelidae)* on "Norland" Potatoes in Manitoba. Entomological Society of America 83(5):2058-2064.

Shotwell, J.A. 1977. The Willapa estuary. Background studies for the preparation of a management plan. Planning Division, Pacific County, Washington.

Shuman, R. 1995-1996. Personal Communication. Metro, Seattle, WA.

Simenstad, C.A., and K.L. Fresh. 1995. Influence of intertidal aquaculture on benthic communities in Pacific Northwest estuaries: scales of disturbance. Estuaries 18:43-70.

Skidmore, L. 1996. Personal Communication. Shoalwater Oysters, Shoalwater, WA/

Smith, M.D. 1996. Manila clam aquaculture in shrimp-infested mudflats. M.Sc. thesis, Oregon State University, Corvallis.

Snelgrove, P. V. R., and C.A. Butman. 1994. Animal-sediment relationships revisited: cause versus effect. Oceanogr. Mar. Biol. Ann. Rev. 32:111-177.

Southwood, T. R. E..,1978. Ecological Methods. Wiley. New York.

Steele, E.N. 1957. The Rise and Decline of the Olympia Oyster. Fulco Publications. Elam, Washington.

Stefanou, S.E. 1984. Pest management concepts -- past present, and future. Farm Economics July/August.

Stern, V.M., R.F. Smith, R. Van den Bosch and K.S. Hagen. 1959. The integrated control concept. Hilgardia 29:81-101.

Stevens, B. A. 1929. Ecological observations on Callianassidae of Puget Sound. Ecology 10:399-405.

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

Stevens, B.A. 1928. Callianassidae from the west coast of North America. Publs. Puget Sound Mar. Biol. Stn. 6:315-369.

Suchanek, T.H. 1983. Control of seagrass communities and sediment distribution by *Callianassa* (Crustacea, Thalassinidea) bioturbation. J. Mar. Res. 41:281-298.

Swinbanks, D. D., and J.W. Murray. 1981. Biosedimentological zonation of Boundary Bay tidal flats, Fraser River Delta, British Columbia. Sedimentology 28:201-237.

Swinbanks, D. D., and J.L. Luternauer. 1987. Burrow distribution of thalassinidean shrimp on a Fraser Delta tidal flat, British Columbia. J. Paleont. 61:315-332.

Tamaki, A. 1994. Extinction of the trochid gastropod, *Umbonium* (*Suchium*) *moniliferum* (Lamarck), and associated species on an intertidal sandflat. Res. Popul. Ecol. 36:225-236.

Tamaki, A., H. Tanoue, J. Itoh, and Y. Fukuda. 1996. Brooding and larval developmental periods of the callianassid ghost shrimp, *Callianassa japonica* (Decapoda: Thalassinidea). J. Mar. Biol. Assoc. U.K. 76:675-689.

Tamaki, A., and B. Ingole. 1993. Distribution of juvenile and adult ghost shrimps, *Callianassa japonica* Ortmann (Thalassinidea), on an intertidal sand flat: intraspecific facilitation as a possible pattern-generating factor. J. Crust. Biol. 13:175-183.

Tamaki, A. 1988. Effects of the bioturbating activity of the ghost shrimp *Callianassa japonica* Ortmann on migration of a mobile polychaete. J. Exp. Mar. Biol. Ecol. 120:81-95.

Tasto, R. N. 1975. Aspects of the biology of Pacific staghorn sculpin, *Leptocottus armatus* Girard, in Anaheim Bay. *In* Lane, E. D., Hill, C. W. (eds). The marine resources of Anaheim Bay. Calif. Fish and Game Fish Bull. 165:135-154.

Taylor, P. 1995. Personal Communication. Taylor Shellfish/Resources, Inc. Shelton, Washington.

Thon, R. 1996-1997. Personal Communication. Battelle Marine Sciencesl Laboratory, Sequim, WA.

Thompson, R.K. 1972. Functional morphology of the hind-gut gland of *Upogebia pugettensis* (Crustacea, Thalassinidea) and its role in burrow construction. Ph.D. Dissertation, University of California, Berkeley.

Thompson, R.K. and A.W. Pritchard. 1969a. Osmoregulatory capacities of *Callianassa* and *Upogebia* (Crustacea: Thalassinidea). Biol. Bull. 136:114-129.

Thompson, R.K., and A.W. Pritchard. 1969b. Respiratory adaptations of two burrowing crustaceans, *Callianassa californiensis* and *Upogebia pugettensis* (Decapoda, Thalassinidea). Biol. Bull. 136:274-287.

Thrush, S.F., R.D. Pridmore, J.E. Hewitt, and V.J. Cummings. 1992. Adult infauna as facilitators of colonization on intertidal sandflats. J. Exp. Mar. Biol. Ecol. 159:253-265.

Tice, E.M. and K. Griffin. 1993. Durability and cost of off-bottom structures for oyster culture in shrimp-infested areas. Final report for the project "The development of engineered alternatives for off-bottom culture in Pacific Coast estuaries where burrowing shrimp infestation precludes traditional oyster bed (bottom) farming". Port of Peninsula, Ocean Park, WA.

Torres, J.J., D.L. Gluck, and J.J. Childress. 1977. Activity and physiological significance of the pleopods in the respiration of *Callianassa californiensis* (Dana) (Crustacea: Thalassinidea). Biol. Bull. 152:134-146.

Tudhope, A.W., and T.P. Scoffin. 1984. The effects of *Callianassa* bioturbation on the preservation of carbonite grains in Davies Reef Lagoon, Great Barrier Reef, Australia. J. Sediment. Petrol. 54:1091-1096.

Tufts, D.F. 1996. Personal Communication. E.H. Bendikson Co.. Nahcotta, WA.

Tufts, D.F. (ed.) 1989. The use of the insecticide sevin to control burrowing shrimp in Willapa Bay and Grays Harbor in 1986. Washington Department of Fisheries. Special Shellfish Report No. 4.

Tufts, D.F., and W. Cooke. 1983. Ghost shrimp - burrow openings/sq yd (shrimp/sq yd). Memo to Ghost Shrimp File, Washington Department of Fisheries, Willapa Bay Shellfisheries Laboratory, Nahcotta, Washington.

Tunberg, B. 1986. Studies on the population ecology of *Upogebia deltaura* (Leach) (Crustacea, Thalassinidea). Estuar. Coast. Shelf Sci. 22:753-765.

U.S. Army Corps of Engineers (USACE). 1976. Willapa River and Harbor navigation project - Washington. Final Environmental Impact Statement. Seattle.

Washington State Department of Agriculture (WSDA). 1988. Water quality sampling data and methodology, Willapa Bay. Washington Department of Agriculture, Dairy and Food Laboratory. Olympia, Washington.

Washington Department of Fisheries (WDF). 1970. Ghost shrimp control experiments with Sevin, 1960-1968. Wash. Dept. Fish. Tech. Rep. 1.

Washington Department of Ecology (WDOE). 1983. Grays Harbor estuary management plan. Program Draft Environmental Impact Statement. Washington State Coastal Zone Management Program, Amendment No. 3.

Washington Department of Fisheries and Washington Department of Ecology (WDF/WDOE). 1985. Use of the insecticide Sevin to control ghost and mud shrimp in oyster beds of Willapa Bay and Grays Harbor. Final Environmental Impact Statement. 88 pp.

Washington Department of Fisheries and Washington Department of Ecology (WDF/WDOE). 1992. Use of the insecticide carbaryl to control ghost and mud shrimp in oyster beds of Willapa Bay and Grays Harbor. Final Supplemental Environmental Impact Statement. 147 pp.

Weitkamp, L.A., R.C. Wissmar, C.A. Simenstad, K.L. Fresh, and J.G. Odell. 1992. Gray whale foraging on ghost shrimp (*Callianassa californiensis*) in littoral sand flats of Puget Sound, U.S.A. Can. J. Zool. 70:2275-2280.

Whitkamp, L. 1996. Personal Communication. School of Fisheries, University of Washington. Seattle, Washington.

Wiegardt, L. 1996. Personal Communication. Jolley Rodger Oyster Co.. Nahcotta, WA.

Williams, G. D. 1994. Effects of a large-scale estuarine intertidal habitat modification on distribution patterns and food habitats of epibenthic fish species in Grays Harbor, Washington. M.Sc. thesis, University of Washington, Seattle, WA.

Wilson, R. 1996. Personal Communication. Bay Center Mariculture. Bay Center, WA.

Wilson, H. W., Jr. 1980. A laboratory investigation of the effect of a terebellid polychaete on the survivorship of nereid polychaete larvae. J. Exp. Mar. Biol. Ecol. 46:73-80.

Witbaard, R., and G.C.A. Duineveld. 1989. Some aspects of the biology and ecology of the burrowing shrimp *Callianassa subterranea* (Montagu) (Thalassinidea) from the southern North Sea. Sarsia 74:209-219.

Woodin, S.A. 1976. Adult-larval interactions in dense infaunal assemblages: patterns of abundance. J. Mar. Res. 34:25-41.

Wynberg, R. P., and G.M. Branch. 1994. Disturbance associated with bait-collection for sandprawns (*Callianassa kraussi*) and mudprawns (*Upogebia africana*): long-term effects on the biota of intertidal sandflats. J. Mar. Res. 52:523-558.

Ziebis, W., S. Forster, M. Huettel, and B.B. Jorgensen. 1996. Complex burrows of the mud shrimp *Callianassa truncata* and their geochemical impact in the sea bed. Nature 382:619-622.

Appendix A.

Forms and Questionnaires Used for Interviews with Oyster Growers and Other Experts

ID #____________________

Integrated Pest Management Plan
Oyster Growers Survey

I. Oyster Farming

A. Background Information

1. How do you grow oysters and what are your markets?

Culture Method	Singles	Shucked Meat	Other
____Long-line	______	______	__________________
____On-bottom	______	______	__________________
____Rack & Bag	______	______	__________________
____Raft	______	______	__________________
____Stake	______	______	__________________
Other____________	______	______	__________________

2. How long have you been growing oysters? ____________________

3. How long has your family been in the business of growing oysters? ______________

C. Growing Schedule

1. What is your annual activity/growing schedule? When are you involved in the following:

   Setting seed

   Transfer oysters to grow-out beds

   Transfer oysters to fattening beds

   Harrowing

   Harvesting

   Sampling shrimp abundance or bed condition

   Controlling shrimp

2. How long (months) does each phase of growing the crop last?

a. On-Bottom Culture
   Seed to grow-out (fattening) transplant ____________________
   Fattening to harvest ____________________
   or Seed to harvest ____________________

b. Long-line Culture
   Seed to harvest ____________________

c. Other culture
   Seed to harvest ____________________

3. Have you intentionally left any of your farmable acreage fallow? (Yes, No)
   If yes:
   a) Why?

   b) What is the maximum time you have left a seed bed fallow (_______ months). Did this affect your recovery of oysters from that bed the next time you farmed it?
      a. Increased recovery
      b. Decreased recovery
      c. No Observable difference

   c) What is the maximum time you have left a fattening bed or long-line bed fallow (_______ months). Did this affect your recovery of oysters from that bed the next time you farmed it?
      a. Increased production
      b. Decreased production
      c. No Observable difference

4. Is Condition Index a useful value for you to predict the quality or yield of your crop?
   a. Crop quality (Yes, No)
   b. Crop yield (Yes, No)
   c. Other ____

D. Geographic Differences

1) Aside from the impact of burrowing shrimp, which geographic areas are better or worse for:

	Seed Beds	**On-Bottom Fattening Beds**	**Long-Line Beds**
Better	______________	______________	______________
Worse	______________	______________	______________

2. On a percentage basis, how much difference in production do you find between locations?

Between Best and Worst Seed Beds __________%

Between Best and Worst Fattening Beds __________%

Between Best and Worst Long-line Beds __________%

3. Is oyster-bed classification a good predictor of yield (disregarding presence of burrowing shrimp)?

II. Managing Burrowing Shrimp

A. Extent of Damage

1. Which species causes the most damage in your oyster beds?
   a. Mud shrimp (*Upogebia*)____________________
   b. Ghost shrimp (*Neotrypaea* [=*Callianassa*])________________
   c. Equal impact__________

2. How does each burrowing shrimp species affect your oyster crop? How do you measure these impacts?

Impact	Ghost	Mud	Measurement
Oysters sink	_______	_______	____________________
Oysters buried	_______	_______	____________________
Beds difficult to work	_______	_______	____________________
Competition for food	_______	_______	____________________
Other______________	_______	_______	____________________

3. What is the proportion of mud and ghost shrimp on your beds?

seed beds............. (_____% mud shrimp, ______% ghost shrimp)

fattening beds........ (_____% mud shrimp, ______% ghost shrimp)

long-line beds........ (_____% mud shrimp, ______% ghost shrimp)

B. Evaluating and Predicting Shrimp Density

1. Who evaluates the density of burrowing shrimp on your oyster beds?

a. Self b. Co-worker/employee c. Expert

If "Expert", skip down to C (pg. 5)

2. How do you currently evaluate present shrimp density?
   1) burrow counts per quadrat
   2) "eyeballed" number of burrow counts
   3) sediment consistency (softness, compaction)
   4) time since bed was last treated
   5) condition of oysters
   6) combination of #__________
   7) other ______________________________

3. Does this method give you accurate information to estimate future shrimp density (Yes, No)?

4. On what basis do you decide to spray a bed?
   1) recommendation of expert
   2) burrow counts per quadrat
   3) "eyeballed" number of burrow counts
   4) sediment consistency
   5) time since bed was last treated
   6) condition of oysters
   7) combination of #__________
   8) other ____

5. If you were taken to a bed that you were unfamiliar with, how many months or years into the future could you judge whether or not that bed would need to be treated?

a. 1-3 months	______	d. 18-21 mo.	______
b. 6-9 months	______	e. 2-2.5 years	______
c. 12-15 mo.	______	f. > 3 years	______

6. How much time must pass for burrowing shrimp density to double or increase 10-fold?

a. Ghost shrimp: increase	2x	______________	10x	______________
b. Mud shrimp: increase	2x	______________	10x	______________

7. At what abundance of shrimp (or condition of oyster beds) is it necessary to apply a control tactic in order to produce a profitable crop?

   a. Seed beds __________________
   b. Fattening beds ________________
   c. Long-line beds ________________
   d. Other culture methods ________________

C. Current Management Practices

1. What proportion of your oyster beds do you currently treat with carbaryl annually?

   a. Seed beds _____________%
   b. Fattening beds _____________%
   c. Long line beds _____________%

2. What proportion of your oyster beds would you like to treat with carbaryl every year?

   a. Seed beds ______________%

   b. Fattening beds ______________%

   c. Long line beds ______________%

3. In your experience, how effective is aerial carbaryl application?
   ______% shrimp are killed on sprayed plot.

4. Which species of shrimp are best controlled by spraying carbaryl (circle one: mud, ghost, both equally, neither)?

5. Has the effectiveness of carbaryl changed over the years?
   a. Yes _________
   b. No _________
   c. No opinion_________

6. What would be the optimum carbaryl-spraying cycle (spraying frequency) that would balance the needs of oyster growing and environmental management?

   a. Spray seed beds every _________________ years.

   b. Spray fattening beds every _________________years.

   c. Spray long-line beds every _________________years.

7. Should the application rate of carbaryl be changed? (Yes, No). If yes, why?

8. Should the application method (areal spraying) for carbaryl be changed? (Yes, No). If yes, why?

9. If use of carbaryl or other pesticides was banned in estuaries, how would oyster farming be affected in Willapa-Grays Harbor?

III. Alternative Management Practices

1. Have you been involved in the design or implementation of any specific alternative burrowing shrimp management practices?
   A. Yes
   B. No

If YES, Please describe the method:

If YES, Please describe how you tested the method
   A. Area applied to

   B. Duration and frequency of application

   C. How success was evaluated

   D. Efficacy (% killed on plot, time for shrimp population to recover)

   E. Cost per acre (relative to cost of spraying with carbaryl: $150/acre)

If NO, Would you be willing to try experimental alternative methods (on a scale of acres)?

2. What alternative control methods or cultural practices do you think show the best promise for future research or development? Why?

3. Do you think that there are constraints (such as regulatory permits or public perceptions) that hinder the use or development of alternative methods to control burrowing shrimp (other than those associated with carbaryl)? What are they?

4. Would you consider another, more environmentally benign, pesticide to be an acceptable alternative to carbaryl for controlling burrowing shrimp? Why or why not?

5. If use of carbaryl (or other pesticides) was banned in estuaries, how would oyster farming be affected in Willapa-Grays Harbor?

IV. Environmental Impacts of Burrowing Shrimp Management

1. What do you think are the short- and long-term benefits of burrowing shrimp management using carbaryl?

A) Short-term benefits?

B) Long term benefits?

2. What do you think are the short- and long-term negative impacts of burrowing shrimp management using carbaryl?

A) Short-term impacts?

B) Long term impacts?

3. Aside from impacts on oyster farming, how does wide-spread high density of burrowing shrimp affect the overall environmental quality of the Willapa-Grays Harbor estuaries?

a) negative impact

b) positive impact

c) neutral impact

d) do not know

4. Are both species of burrowing shrimp equally detrimental or beneficial?

5. What natural resources are negatively affected by high densities of burrowing shrimp?

6. What natural resources benefit from high densities of burrowing shrimp?

7. In what ways does oyster farming have a beneficial impact on the overall environmental quality or natural resources of the Willapa-Grays Harbor estuaries?

8. In what ways does oyster farming negatively impact the overall environmental quality or natural resources of the Willapa-Grays Harbor estuaries?

9. If oyster farming has any detrimental impact on the estuary, what aspects of the farming practices have the greatest negative impact?

On Bottom

Long-line

Rack and Bag

Other Method

10. In what ways can oyster farming change to improve its affects on the environmental quality and natural resources of Willapa-Grays Harbor?

11. In what ways can the local community, the State, or Federal government help oyster farmers reduce negative impacts they may exert in the estuary?

12. In what ways can the local community, the State, or Federal government help oyster farmers control burrowing shrimp?

Integrated Pest Management Plan
Oyster Growers Survey

Take Home Portion

1. Oyster Grower Costs and Revenues Survey
2. Survey on Effectiveness and Feasibility of Methods to Control Burrowing Shrimp
3. Survey on Impacts of Control Methods
4. Carbaryl Risk Survey

By November 9, Please Return to:

Ted DeWitt
Battelle Marine Science Laboratory
1529 W. Sequim Bay Rd.
Sequim, WA 98382

phone: (360) 681-3656
fax: (360) 681-3681

Integrated Pest Management Project - Oyster Grower Costs and Revenues Survey

Instructions: To the best of your ability, please provide the following economic information regarding your oyster growing operation. We would very much like to have this information for as many of the last five years as you can provide. If you only have information on the average across years, please fill in one column and indicate the number of years for which this average pertains (write this in one of the grey-shaded rows). Attached is a list of the same questions in expanded form to help you understand what we seek.

	Farm Size	Units of Measure Circle One	1990	1991	1992	1993	1994
1	Total Acres Farmed	acres					
2	Total Acres Owned (not leased)	acres					
3	Total Acres Used for On-Bottom Culture	acres					
4	Total Acres Used for Long-Line Culture	acres					
5	Total Acres Used for Seed Beds	acres					
6	Total Acres Used for Other Culture Methods	acres					
7	Total Acres Not Farmed, On Average	acres					
	Costs						
8	Total Combined Annual Costs	$/bushel or $/acre					
9	Costs for Value-Added Activities	$/bushel or $/gal					
10	Variable Costs of Production	$/bushel or $/acre					
11	Fixed Costs of Production	$/bushel or $/acre					
12	Investment Costs of Production	$/bushel or $/acre					
	Burrowing Shrimp Control						
13	Total Acres Treated By Any Method	acres					
14	Total Acres Treated with Carbaryl	acres					
15	Total Farmed Acres Not Treated with Anything	acres					
16	Farmable Acres That Should Have Been Treated	acres					
17	Total Cost to Control Shrimp	$/bushel or $/acre					
18	Cost to Control Shrimp Using Carbaryl	$/bushel or $/acre					
19	Annual Loss Due to B. Shrimp	$/bushel or $/acre					
20	Cost to Sample Shrimp Abundance	$/bushel or $/acre					
	Harvest Income						
21	Total Annual Yield	gal/acre or bushel/acre					
22	Total Annual Return	$/gal or $/acre					
	Conversion Factors						
23	Gallons of Meat per Bushel of Oysters	number					

ID# ___ ___ ___

Oyster Grower Costs and Revenues Survey

Expanded list of questions. These questions are intended to help you better understand the data we need to collect to conduct an econmic analysis of the impact of burrowing shrimp on oyster farming and to develop economic threshold models for the IPM strategy. Please answer these questions on the table provided.

1. What is the total tideland acreage of your operation?

2. How many tideland acres do you own (not leased)?

3. How many tideland acres do you use for on-bottom oyster culture?

4. How many tideland acres do you use for long-line oyster culture?

5. How many tideland acres are used for seed beds for on-bottom culture?

6. How many tideland acres are used for other methods of oyster culture?

7. How many tideland acres are unfarmed on average per year?

8. List your total combined annual costs (labor, material and services, capital, other) of oyster production in terms of $/bushels or $/acre (not both).

9. List your total costs for value-added activities in terms of $/bushels or $/acre (not both).

10. Of your total costs, please list all your variable costs of production (stake and mark, seeding, transplanting, cut and set pipe, string oysters, setting lines, repair pipe and lines, rake oysters, tribal, bookkeeping, equipment, permits, overhead, interest on operating capital) in terms of $/bushel or $/acre (not both).

11. Of your total costs, please list all fixed costs of production (depreciation, interest, land charge, shrimp treatment, establishment investment interest) in terms of $/bushels or $/acre (not both).

12. List your total investment costs of production in terms of $/bushels or $/acre (not both).

13. How many acres were treated for burrowing shrimp each year (all control methods combined)?

14. How many acres were treated with carbaryl?

15. How many of your farmed acres were untreated with carbaryl?

16. Of these farmed but untreated acres, how many should have received some sort of treatment because burrowing shrimp density was (or would become) high enough to affect your oyster crop within one year?

17. List the cost to control burrowing shrimp (by all methods used) in terms of $/bushels or $/acre (not both).

18. List the cost to control burrowing shrimp using carbaryl in terms of $/bushels or $/acre (not both).

19. List your annual economic losses due to the presence of burrowing shrimp in terms of gallons/acre or $/acre (not both).

20 . List your annual costs to sample burrowing shrimp abundance on your oyster beds in terms of $/bushel or $/acre (not both).

21. What was your annual yield in terms of gallons/acre or bushels/acre (not both)?

22. What was your annual return in terms of gallons/acre or $/gallons (not both)?

23. On average, how many gallons of oyster meat were produced per bushels of oysters?

ID#____________________

Integrated Pest Management Plan
Non-Growers Survey

1. Have you farmed oysters? (Yes, No)
   If Yes,

   a) For how long and when?

   b) What culture methods: (Bottom, long-line, rack & bag, other____________________)

   c) Did you have to control burrowing shrimp?

   d) What methods did you use to control the shrimp?

2. Have you had direct experience working with burrowing shrimp, either to manage their abundance or to understand their biology? (Yes, No)

If Yes, continue with next section. Otherwise, skip to Part III (pg 3)

II. Burrowing Shrimp Impact & Control

A. Extent of Damage

1. Which species causes the most damage in oyster beds?
   a. Mud shrimp (*Upogebia*)____________________
   b. Ghost shrimp (*Neotrypaea* [=*Callianassa*])____________________
   c. Equal impact____________________

B. Evaluating and Predicting Shrimp Abundance

1. What is the best method to evaluate present shrimp density?
   1) burrow counts per quadrat
   2) "eyeballed" number of burrow counts
   3) sediment consistency
   4) time since bed was last treated
   5) condition of oysters
   6) combination of #__________
   7) other ______________________________

2. Does this method give you accurate information to estimate future shrimp abundance
(Yes, No)

3. If you were taken to a bed that you were unfamiliar with, how many months or years into the future could you judge whether or not that bed would need to be treated?

a. 1-3 months	______	d. 18-21 mo.	_______
b. 6-9 months	______	e. 2-2.5 years	_______
c. 12-15 mo.	______	f. > 3 years	_______

5. How much time must pass for burrowing shrimp abundance to double or increase 10-fold?

a. Ghost shrimp: increase 2x ________________ 10x ________________

b. Mud shrimp: increase 2x ________________ 10x ________________

6. At what abundance of shrimp (or condition of oyster beds) is it necessary to apply a control tactic in order to produce a profitable crop?

a. Seed beds ____________________

b. Fattening beds ________________

c. Long line beds_________________

C. Current Management Practices

1. In your experience, how effective is aerial carbaryl application?
______% shrimp are killed on sprayed plot.

2. Which species of shrimp are best controlled by spraying carbaryl? (mud, ghost, both equally, neither)

4. Has the effectiveness of carbaryl changed over the years?

a. Yes _________

b. No _________

c. No opinion_________

d. Ask growers

5. What would be the optimum carbaryl-spraying cycle (spraying frequency) that would balance the needs of oyster growing and environmental management?

a. Spray seed beds every ________________ years.

b. Spray fattening beds every ________________years.

c. Spray long-line beds every _________________years.

6. Should the application rate of carbaryl be changed? (Yes, No). If yes, why?

7. Should the application method (areal spraying) for carbaryl be changed? (Yes, No). If yes, why?

III. Alternative Management Practices

1. What alternative control methods do you think show the best promise for future research or development? Why?

2. Do you think that there are constraints (such as regulatory permits or public perceptions) that hinder the use or development of alternative methods to control burrowing shrimp (other than those associated with carbaryl)? What are they?

3. Would you consider another, more environmentally benign, pesticide to be an acceptable alternative to carbaryl for controlling burrowing shrimp? Why or why not?

4. If use of carbaryl (or other pesticides) was banned in estuaries, how would oyster farming be affected in Willapa-Grays Harbor?

IV. Environmenal Impacts of Burrowing Shrimp Management

1. What do you think are the short- and long-term benefits of burrowing shrimp management using carbaryl?

A) Short-term benefits?

B) Long term benefits?

2. What do you think are the short- and long-term negative impacts of burrowing shrimp management using carbaryl?

A) Short-term impacts?

B) Long term impacts?

3. Aside from impacts on oyster farming, how does wide-spread high density of burrowing shrimp affect the overall environmental quality of the Willapa-Grays Harbor estuaries?

a) negative impact

b) positive impact

c) netural impact

d) do not know

4. Are both species of burrowing shrimp equally detrimental or beneficial?

5. What natural resources are negatively affected by high densities of burrowing shrimp?

6. What natural resources benefit from high densities of burrowing shrimp?

7. In what ways does oyster farming have a beneficial impact on the overall environmental quality or natural resources of the Willapa-Grays Harbor estuaries?

8. In what ways does oyster farming negatively impact the overall environmental quality or natural resources of the Willapa-Grays Harbor estuaries?

9. If oyster farming has any detrimental impact on the estuary, what aspects of the farming practices have the greatest negative impact?

On Bottom

Long-line

Rack and Bag

Other Method

10. In what ways can oyster farming change to improve its affects on the environmental quality and natural resources of Willapa-Grays Harbor?

11. In what ways can the local community, the State, or Federal government help oyster farmers reduce negative impacts they may exert in the estuary?

12. In what ways can the local community, the State, or Federal government help oyster farmers control burrowing shrimp?

Integrated Pest Management Plan
Non-Growers Survey

Take Home Portion

1. Survey on Impacts of Control Methods
2. Carbaryl Risk Survey

By November 9, Please Return to:

Ted DeWitt
Battelle Marine Science Laboratory
1529 W. Sequim Bay Rd.
Sequim, WA 98382

phone: (360) 681-3656
fax: (360) 681-3681

IPM Project: Survey on Impacts of Control Methods

Instructions: For each method used (or proposed) to control burrowing shrimp, please rate the LONG TERM effect that it would have on environmental and human resources.
Rate impacts on a scale of 1 (= very detrimental impact) to 10 (= very beneficial impact)

Control Method	Water Quality and Debris	Mammals	Birds	Fish	Benthic Invertebrates	Eelgrass	Short-term Human Health Effects	Long-term Human Health Effects	Recreational Revenues, Jobs, or Income	Fishery Revenues, Jobs, or Income	Overall Economic Effects
Carbaryl Pesticide											
Other Pesticides											
Enhance Shrimp Predators											
Develop Silt-resistant Oysters											
Cover Beds with Plastic Sheet or Mesh											
Mechanical Compaction of Substrate											
Inject Clay into Burrows											
Shell or Gravel Pavement											
Explosives											
Harrowing											
High or Low Pressure Water Jets											
Electroshocking or Ultrasound											
Harvest Shrimp											
Other:											
Other:											

ID#_ ____ ____

Carbaryl Risk Survey

I. Risk Ranking

Please rate how important you believe it is to reduce or avoid risk from the use of carbaryl in each of the following areas. Please circle the appropriate number.

Environmental Area at Risk	Importance (1-10) Not Important									Very Important
1. Surface water	1	2	3	4	5	6	7	8	9	10
2. Fish (estuarine species)	1	2	3	4	5	6	7	8	9	10
3. Birds (waterfowl, birds of prey, seabirds)	1	2	3	4	5	6	7	8	9	10
4. Invertebrates (crabs, worms, benthic species)	1	2	3	4	5	6	7	8	9	10
5. Mammals (land and aquatic)	1	2	3	4	5	6	7	8	9	10
6. Plants (eelgrass)	1	2	3	4	5	6	7	8	9	10
7. Endangered species (threatened plants and animals)	1	2	3	4	5	6	7	8	9	10
8. Yourself and others (poisoning)	1	2	3	4	5	6	7	8	9	10
9. Chronic (long term) health effects to yourself/family	1	2	3	4	5	6	7	8	9	10

II. Cost of Avoiding Risk

One way to address the environmental risks (in particular) from the use of carbaryl is to understand how much people are willing to pay to avoid certain levels of risk. By putting a dollar value on avoiding these risks, we can identify how much more people would be willing to pay for the development of safer pesticides with less negative environmental impacts or how much greater yield losses producers would be willing to tolerate to avoid carbaryl use.

The average cost of carbaryl treatment is $150 per acre (including application and material costs). An oyster producer may be willing to spend additional amounts to reduce or avoid the environmental impacts of carbaryl application. In practice, these additional costs might take the form of a premium for a more benign pesticide or as greater yield losses that would be tolerated to avoid carbaryl use.

A. Oyster Growers

1) Approximately how much did you spend on carbaryl in 1994, including application costs?

$________________/acre

2) For one application of carbaryl, what would you be willing to spend or accept in yield losses to avoid risk from carbaryl? Please provide an answer for each level of risk:

a. to avoid high risks to the environment $________/acre
b. to avoid moderate risks to the environment $________/acre
c. to avoid low risks to the environment $________/acre

3) Who should pay for this cost and why?

a. Growers

b. Local community in Willapa Bay or Grays Harbor

c. State or Federal government

d. Shared among all of the above

B. Non-Growers

1) For one application of carbaryl, what would you be willing to spend to avoid risk from carbaryl? Please provide an answer for each level of risk:

a. to avoid high risks to the environment $________/acre
b. to avoid moderate risks to the environment $________/acre
c. to avoid low risks to the environment $________/acre

2) Who should pay for this cost?

a. Growers

b. Local community in Willapa Bay or Grays Harbor

c. State or Federal government

d. Shared among all of the above

IPM Project: Survey on Effectiveness and Feasibility of Methods to Control Burrowing Shrimp

Instructions: For each method used (or proposed) to control burrowing shrimp, please rate:

1) Effectiveness at reducing burrowing shrimp density relative to the effectiveness of carbaryl.
   + : method is likely to be MORE effective as carbaryl
   -- : method is likely to be LESS effective than carbaryl
   = : method is likely to be ABOUT EQUALLY effective as carbaryl
   U : Uncertain about how effective method would be
2) Technical feasibility of developing and using the control method on a large scale (100+ acres/yr).
   0 : development of technology is highly unlikely and success is unlikely.
   1 : development of technology is possible, but success is doubtful;
   2 : technology exists and success is possible
   3 : technology exists and success proven (carbaryl would = 3).
   U : Uncertain about availability of technology or likely success
3) Cost (per acre) of applying the control method relative to the cost of carbaryl.
   + : cost is likely to be MORE than carbaryl
   -- : cost is likely to be LESS than carbaryl
   = : cost is likely to be ABOUT EQUAL to carbaryl
   U : Uncertain about cost relative to carbaryl
4) Your experience working with the control method.
   0 : No Experience
   1 : Tried experimentally on a small scale
   2 : Used on some oyster beds
   3 : Used regularly on more than 1 bed

Control Method	Effect on Shrimp	Technical Feasibility	Cost	Personal Experience
Pesticides (Other than Carbaryl)				
Enhance Predators				
Develop Silt-resistant Oysters				
Cover Beds with Plastic Sheet or Mesh				
Mechanical Compaction of Substrate				
Inject Clay into Burrows				
Shell or Gravel Pavement				
Explosives				
Harrowing				
High or Low Pressure Water Jets				
Electroshocking or Ultrasound				
Harvesting Shrimp				
Other:				
Other:				

IPM Project: Survey on Impacts of Control Methods

Instructions: For each method used (or proposed) to control burrowing shrimp, please rate the LONG TERM effect that it would have on environmental and human resources.
Rate impacts on a scale of 1 (= very detrimental impact) to 10 (= very beneficial impact)

Control Method	Water Quality and Debris	Mammals	Birds	Fish	Benthic Invertebrates	Eelgrass	Short-term Human Health Effects	Long-term Human Health Effects	Recreational Revenues, Jobs, or Income	Fishery Revenues, Jobs, or Income	Overall Economic Effects
Carbaryl Pesticide											
Other Pesticides											
Enhance Shrimp Predators											
Develop Silt-resistant Oysters											
Cover Beds with Plastic Sheet or Mesh											
Mechanical Compaction of Substrate											
Inject Clay into Burrows											
Shell or Gravel Pavement											
Explosives											
Harrowing											
High or Low Pressure Water Jets											
Electroshocking or Ultrasound											
Harvest Shrimp											
Other:											
Other:											

Carbaryl Risk Survey

I. Risk Ranking

Please rate how important you believe it is to reduce or avoid risk from the use of carbaryl in each of the following areas. Please circle the appropriate number.

Environmental Area at Risk	Importance (1-10) Not Important									Very Important
1. Surface water	1	2	3	4	5	6	7	8	9	10
2. Fish (estuarine species)	1	2	3	4	5	6	7	8	9	10
3. Birds (waterfowl, birds of prey, seabirds)	1	2	3	4	5	6	7	8	9	10
4. Invertebrates (crabs, worms, benthic species)	1	2	3	4	5	6	7	8	9	10
5. Mammals (land and aquatic)	1	2	3	4	5	6	7	8	9	10
6. Plants (eelgrass)	1	2	3	4	5	6	7	8	9	10
7. Endangered species (threatened plants and animals)	1	2	3	4	5	6	7	8	9	10
8. Yourself and others (poisoning)	1	2	3	4	5	6	7	8	9	10
9. Chronic (long term) health effects to yourself/family	1	2	3	4	5	6	7	8	9	10

II. Cost of Avoiding Risk

One way to address the environmental risks (in particular) from the use of carbaryl is to understand how much people are willing to pay to avoid certain levels of risk. By putting a dollar value on avoiding these risks, we can identify how much more people would be willing to pay for the development of safer pesticides with less negative environmental impacts or how much greater yield losses producers would be willing to tolerate to avoid carbaryl use.

The average cost of carbaryl treatment is $150 per acre (including application and material costs). An oyster producer may be willing to spend additional amounts to reduce or avoid the environmental impacts of carbaryl application. In practice, these additional costs might take the form of a premium for a more benign pesticide or as greater yield losses that would be tolerated to avoid carbaryl use.

A. Oyster Growers

1) Approximately how much did you spend on carbaryl in 1994, including application costs?

$________________/acre

2) For one application of carbaryl, what would you be willing to spend or accept in yield losses to avoid risk from carbaryl? Please provide an answer for each level of risk:

a. to avoid high risks to the environment $_______/acre
b. to avoid moderate risks to the environment $_______/acre
c. to avoid low risks to the environment $_______/acre

3) Who should pay for this cost and why?

a. Growers

b. Local community in Willapa Bay or Grays Harbor

c. State or Federal government

d. Shared among all of the above

B. Non-Growers

1) For one application of carbaryl, what would you be willing to spend to avoid risk from carbaryl? Please provide an answer for each level of risk:

a. to avoid high risks to the environment $_______/acre
b. to avoid moderate risks to the environment $_______/acre
c. to avoid low risks to the environment $_______/acre

2) Who should pay for this cost?

a. Growers

b. Local community in Willapa Bay or Grays Harbor

c. State or Federal government

d. Shared among all of the above

Appendix B.

Analysis of Interview Responses Given by Oyster Growers and Non-Grower Experts

Summary

Twelve oyster growers and eight non-growers from Willapa Bay and Grays Harbor were surveyed during in-person interviews and given a follow-up questionnaire to fill out at their leisure. Six of each type of take home survey were returned to Battelle. Growers and non-growers were questioned regarding their involvement and practices in the oyster industry, in particular dealing with their management of the pest species known as burrowing shrimp. Many questions dealt specifically with the environmental and social impacts of the most common management tool for controlling the shrimp, the aerial spray application of the pesticide carbaryl. The vast range of responses indicated not only differences between growers and non-growers, but differences within these groups as well. Inconsistencies were also noted between various aspects of the survey responses from certain individuals. However, a significant area of common ground among all respondents was found, as were areas where knowledge gaps and uncertainties were the most common factor. The responses highlight a great deal of frustration at the current state of affairs, with polarization and distrust a hallmark of most stakeholders, at least at some point in each discussion. The group of stakeholders is rather large, encompassing the two surveyed groups, the local community, state and federal regulatory agencies, academic institutions, as well as seafood consumers and other interested parties outside of the local region. The use of the pesticide carbaryl is a contentious issue, with an uncertain future. However, no obvious replacement shows any real sign of playing a role in controlling burrowing shrimp the near future. This survey is an important start in designing an integrated pest management plan that can gain acceptance by a large percentage of the stakeholder assemblage.

1. Oyster Farming

A. Background Information

Of the twelve growers surveyed, eight grow oysters using the on-bottom method, of which six are only bottom growers and the other two have some long-line operations. Five growers, including the two already mentioned, used a long-line method; one grower used a rack and bag technique. The majority of the bottom cultured oysters are harvested for shucked meat, which is presumably shipped in bulk to canneries. Some singles are also harvested using bottom culture. The majority of the long-line oysters are sold as singles (whole oysters) to the restaurant and carryout markets, however some long-line growers provide bulk and bushels to the canneries. The rack and bag grower produces single shell stock.

Four growers have been in business longer than 20 years, with two operations having a lengthy family history in this business. One grower reports a family history of five generations, dating back to 1874. Six growers have been in business for 10 - 20 years, with two having family history of growing. The other two are relatively new to the industry, operating for less than 10 years. More than half of the growers had no reported family history in the industry.

B. Growing Schedule

On-bottom growers set seed during spring and summer, during the period of April to September. This may be done early if the grower is running a hatchery. Late set seed will be left to overwinter until the next spring. Weather conditions play a factor in determining when to set out seed. Some growers use a mix of hatchery seed and natural setting, while one grower indicates that all his oyster production is a result of natural seed set. The long-liners string oysters on ropes starting in February when the weather permits, and most set seed during the spring, although some will do this during the summer months as well.

Transfer of oysters to grow-out beds (planting) and fattening beds (transplanting) depends on the depth of water and the susceptibility of the area to storms, according to one grower. Others may be induced to transfer if shrimp density threatens particular beds with large losses, or to allow oysters to fatten if high shrimp densities are competing with the oyster crop for food. Some growers, especially long-liners, do not transfer the oysters at all. Planting most often occurs in the spring the year following seed set, and may continue into the summer. Planted seed may be allowed to lay over for two summers. Transfer to fattening beds occurs when the oysters are large enough, by picking or dredging, mostly by the on-bottom growers. This may be done year round. At this point the oysters are approximately two and a half years old.

Harrowing may be done prior to harvest to get the oysters positioned on top of the sediment, mostly in September to October. Harrowing may also be done to the newly set seed after approximately one month, and some on-bottom growers harrow in the spring. Long-liners may harrow after the structures are removed to smooth out collected sediment.

On-bottom and long-line harvesting is done throughout the year, but the peak season is the fourth quarter, October through December. This coincides with the peak marketing season which starts in early January. For some long-liners the peak harvesting times are during the winter and spring months.

Many growers indicated that they sample shrimp abundance and monitor bed condition on a continual basis, although the peak season is spring. This allows them to identify beds that need spraying in time to spray in mid-summer. Growers prefered to spray beds before seed is set so that the young oyster will not be immediately lost. Other growers indicate that they spray beds which have just been harvested, as the presence of oysters on the beds may serve to mask the shrimp abundance. Growers note that they are forced to spray for shrimp in late June and early July by the regulatory agencies. Many would prefer to spray in fall when the shrimp are most active as well as recruiting to the beds, although some would like to spray in the spring before they set seed. On-bottom culture takes approximately three to four years from seed set to harvest. Long-line culture takes approximately one year less on average.

Only two growers reported leaving any farmable acreage fallow. One bottom grower left low quality acreage with high shrimp density unused. A long-liner used crop rotation, leaving some areas fallow, to increase crop productivity. Another grower, who skipped this question, later indicated that he only farms 30% of his acreage because the rest was infested with shrimp. This may indicate that infested areas are not considered "farmable".

The condition index is useful to less than half of the growers for predicting crop quality or yield. However, those who do find it useful are predominantly the on-bottom growers, and more so for quality than for yield. Two growers noted that the index is only useful for short term predictions. It is primarily the long-liners who do not use the condition index either for yield or quality. Three respondents had either never used the index or skipped the question. One grower notes a long term decline in the condition index, and wonders whether the chemical treatment could be to blame.

C. Geographic Differences

According to one grower, as only two reported on this section completely, high ground in the southern part of Willapa Bay is the best seed bed area as it catches natural set and has warmer water temperatures. Seed beds may have variation in yields of 100%. Stony Point, near South Bend, and areas near the mouth of the bay have the best fattening beds, while the worst for this function is toward the center of the bay. Production yields may vary by 40%. Other research by this writer has indicated fattening beds are best in areas of high nutrient availability, as this provides a rich food source. The best areas for long-line operations are variable, although sometimes growers are driven to off-bottom culture by the unsuitability of the bottom substrate for on-bottom culture. Long-line yields may vary by 45% depending on location, as well as seasonal factors.

Four of the bottom growers thought that bed classification is a good predictor of oyster yield, one did not. The long-liners either indicated that the classification is not a good predictor of yield, or skipped the question, indicating that this is not applicable to their operations. One noted that marginal land receives low classification rank, and this is a primary reason for using long-line method.

II. Managing Burrowing Shrimp

A. Extent of Damage

There is general agreement among growers that the ghost shrimp cause most of the damage to the oyster beds, with one grower not sure and another indicating mud and ghost cause equal damage, but in different ways. Some growers indicated that ghost shrimp are more active in bioturbation and tunnel excavation. Others indicated that the presence of mud shrimp is not incompatible with oyster growth, but may cause long-term production decreases. Some thought that ghost shrimp "follow" mud shrimp in colonizing beds.

Only half of the non-growers responded to this question, with responses split between ghost shrimp and both species equally. Two non-growers strongly objected to this line of questioning that distinguishes between "good" and "bad" classifications of organisms. To these individuals, the shrimp represent ecosystem constituents that are evolutionarily adapted to this estuarine environment, and they are unwilling to take a "pest perspective" of the shrimp verses the exotic cultivated Pacific oyster.

The proportional distribution of the two shrimp species is variable depending on location and the proportion of beds used for different growing activities. Some growers reported that mud shrimp predominates in the beds newly seeded, while ghost shrimp predominate in beds used for fattening. This may relate to conditions and areas where growers choose to locate various phases of their operations. Areas suitable for seed beds are often in locations of mud shrimp habitat, while fattening beds are more often better habitat for ghost shrimp. (Ghost shrimp prefer sandy, higher tidal elevation areas, whereas mud shrimp prefer lower tidal elevation, muddy areas.) If a growers' acreage is primarily composed of one habitat type, then that particular species will be more abundant. More than half of the growers reported that mud shrimp were the dominant pest species on their beds.

Problems caused by ghost shrimp activity mostly involve oysters sinking into the substrate or becoming buried by silt, as well as creating difficult working conditions on the beds due to liquefying the substrate. Some growers note that ghost shrimp may compete with the oysters for food, or decrease the growth of eelgrass. Sinking and buried oysters was also noted in relation to mud shrimp, but to a lower extent than with ghost shrimp. More growers indicated that mud shrimp compete more with the oysters for food which results in skinnier oysters, and create difficult working conditions on the beds for workers and equipment. Some respondents noted that mud shrimp presence is manageable, either by avoiding infested areas or utilizing alternate techniques, such as long-lining. Overall long-liners are less affected by the presence of either shrimp species.

B. Evaluating And Predicting Shrimp Density

Most of the growers (10) inspect for the presence of shrimp themselves, several also allowed co-workers or employees to do this. Although experts inspect beds for 4 of the growers, it is often after the grower has made an evaluation of the most infested areas. Shrimp density is most commonly evaluated on the basis of sediment consistency and burrow counts, either by quadrat or through "eyeballing". Half of those responding thought that this information could be used to estimate shrimp density, others thought density had more to do with location, climatic factors or shrimp recruitment.

The non-growers responding to this inquiry indicated that while burrow abundance and sediment consistency could be used as density indicators, three individuals favored direct sampling methods, such as the use of a fixed time/area pump, with the data correlated with location, intertidal height and substrate type. Another non-grower suggested the use of ground penetrating radar or other acoustical monitoring methods. Only two non-growers responded regarding the predictive accuracy of methods, and only regarding burrow abundance measurements. One indicated that this method could not be used to estimate shrimp density, and the other did not know.

Growers primarily base their decision to spray on the recommendation of an expert, who mostly used burrow counts and sediment consistency as indicators of need. Several growers base their spray decisions on the amount of time passed since last spraying or on the condition of the oyster crop. Two growers indicated their basis was on whether they received a spray allotment, and one grower reported that he does not spray based on the wishes of the land owner.

Only two growers indicated that they could judge the future spray needs of an unfamiliar bed, and of these, only for approximately 1 year into the future. One non-grower thought spray needs could be predicted for 12-15 months. One non-grower reported that prediction of the need to spray is unnecessary for the reason that spraying itself is not needed when conditions exist that are antithetical to shrimp, such as the presence of eelgrass. Eight growers had no idea of the length of time required for populations of either species to double or increase by a factor of ten. The other four thought it takes approximately 1-2 years for populations to double. Only one non-grower would hazard a guess, of approximately one season. Other non-growers thought the time needed for populations to double is based on environmental conditions, or pointed out that the issue is recruitment not migration. No growers responded to the question of what shrimp abundance or oyster condition necessitated shrimp control. One non-grower indicated that he did not know. Of the twelve growers, all reported some problems relating to shrimp infestation, and only one characterized the problem as "low infestation".

C. Current Management Practices

The proportion of beds reported to receive annual treatment was quite variable. Four farmers treat 25% or less of their seed beds annually, and two others indicating 3 year cycles for treatment. One farmer reported that he treats 60-70% of his seed beds annually. One grower treats 25% of his fattening beds annually, another only 5%, with several others noting these beds can't be sprayed as they contain oyster that are to be harvested within 1 year. Long-liners are also variable with two growers reporting no annual spraying, two at 10-20% annually, and 1 working a 3 year cycle. Four growers indicated that they would prefer to spray when the beds appeared to need it, rather than annually or on a predetermined cycle. Three growers would like to spray 100% of their beds annually, and another three 33% or less annually. One grower would like to see the whole bay treated to eradicate shrimp every 25 years.

Five growers thought that aerial spraying was effective at killing over 90% of shrimp present on a bed. Two thought the effectiveness was 70-90%. Three non-growers thought the effectiveness was high. Three growers use hand application or other methods, and thought that the effectiveness was significantly lower than aerial spraying. More than half of the growers thought that both shrimp species are controlled equally well, two thought mud shrimp are controlled better than ghost by the spray, and two have no idea. Two non-growers thought ghost shrimp are controlled best by spray, and one thought any shrimp near the surface will be impacted. All respondents who had an opinion (11), thought that the effectiveness has not changed over the past years of use. No growers responded to the question regarding the optimum spray frequency to balance oyster production and environmental management. One non-grower indicated that better methods of quantifying shrimp populations are necessary, as is the quantification of pest densities sufficient to demand pesticide application. He expressed a need to correlate treatment efforts and pest densities with oyster production, in order to optimize the spray frequency.

Six growers indicated that the application rate should not be changed. The four who did were split between one wanting to lower the rate, two to test whether a lower rate was effective, and one who wanted the rate increased. Half of the non-growers thought the application rate should be changed, with three wanting it lowered, and one wanting the rate changed so that a one time application would be most effective at killing shrimp. At least three growers and two non-growers noted that the timing of the application is in need of change, which was not addressed by the survey. Seven of the growers thought that aerial application method should not be changed, while others thought that helicopter spraying should be curtailed or application methods be more suited to the size and location of beds. One non-grower strongly suggested that all control efforts should be aimed at the juvenile shrimp only, and that many current problems were the result of attempting to control adults.

Almost all growers thought that the industry would be negatively affected if carbaryl was banned, although the severity of the response was variable. Some indicated that uninfested areas would continue to be farmed, but with a loss of revenue and employment. Others thought that the "industry as we know it" would vanish. Long-liners as well as ground growers indicated that they would be negatively affected. One respondent thought Grays Harbor would be hit harder than Willapa Bay.

At least half of the non-growers also thought that the industry would suffer if carbaryl use was banned, with both farmable acreage and economic returns to the industry declining. Overall, non-growers thought that the industry would continue, but at a decreased level. Some who thought that the industry would lose growers indicated that the estuary would lose "ecosystem guardians", growers who supported high water quality conditions and a curb on development. Banning the chemical would provide the incentive to develop alternative shrimp control measures, as well as alternative growing methods, according to some. Two non-growers cited Oregon as an example of what would occur should carbaryl be banned, although one indicated that the Oregon industry was still viable, and the other pointing to the demise of the industry in Tillamook Bay. One person suggested that with carbaryl banned the covert, illegal use would skyrocket with the unregulated application rate also increased.

III. Alternative Management Practices

Six growers reported that they have been involved in alternative management practices in the past. Activities included the use of ground cover such as plastic sheeting and mechanical devices typically used to crush the shrimp on the beds. Some growers experimented with alternative uses of carbaryl both in the level of application as well as the method of delivery to the beds. Another has experimented with alternative chemicals including nicotine. Some long-liners indicated that off-bottom culture methods should be considered alternatives to the more common ground culture technique. All of the growers who answered(10) indicated that they are willing to consider more benign alternatives to carbaryl, as long as both the effectiveness and the benign character could be demonstrated. All eight of the non-growers indicated a similar willingness although two noted that they thought that the use of carbaryl was not all that bad.

The growers had a wealth of ideas for possible alternative management strategies in addition to the methods listed above, although one responded that he had not heard of anything that could replace carbaryl. One grower indicated that this topic was one that growers discussed often. Alternative chemicals could be introduced, but they would necessarily have to be of a narrow spectrum to only affect shrimp. An example would be a substance that retards the maturation of shrimp, or renders them sterile. Alternative delivery methods for the application of carbaryl or other chemicals was suggested. Several growers thought that a long term solution is preferable to treating the short term effects. They advocate an ecosystem approach to the estuaries based on restoring a balance of predators such as several species of finfish. To this end they advocate the elimination of the baitfish harvest, and the reduction of seal abundance to reduce pressure on the fish. Other forms of biological control were suggested including the introduction of bio-agents such as diseases or parasites affecting shrimp. Another alternative is the introduction of sterile shrimp or those with genetic modifications that would affect the general shrimp populations. Only one or two growers had confidence in mechanical eradication, suggesting that these methods caused considerable damage to the benthic conditions. One grower suggested pumping the shrimp out of the beds. The shrimp could be left as food for gulls or sold for bait. Two growers suggested that shrimp control is needed less when oyster growing methods can coexist with the presence of shrimp. They noted that off bottom methods such as floating pens or structures above the bottom are less affected by shrimp presence.

Half of the non-growers advocate some form of biological control, often with the stated purpose of re-establishing a measure of ecological balance they thought was currently lacking in the estuarine system. Suggestions included shrimp predator enhancement, shrimp parasites, diseases, growth inhibitors and substances that might alter shrimp reproductive behavior. Alternative off-bottom growing methods were suggested by two respondents, with one noting a platform technique apparently successfully used in Australia. Substrate enhancement was suggested for continued bottom culture farmers, either using a tarp or mesh layer, or through the use of shell, which may also attract crabs. While two individuals suggested mechanical methods that would crush the shrimp in the beds, another favored reducing the level of disturbance, especially to any eelgrass that may occur on the beds. Other suggestions include the development of a more narrow spectrum of chemicals, and the pumping of live shrimp from the beds to use as bait.

The most common hindrance to the development of alternative management practices cited by the growers was the actions and attitudes of government agencies responsible for regulations in the estuarine areas. Growers noted that the permitting process for alternative management methods restricts their implementation, and suggested that the agencies do not give the growers much priority for experimenting with alternative control methods, relative to concerns for the protection of habitat or eelgrass beds. Another factor hindering alternatives development is the overall cost of new techniques, especially in relation to the marginal economics of the oyster market. Other hindrances include a lack of research into alternatives and the reaction of neighbors and the public to new control methods, which often can not be predicted until they are implemented. Perhaps the most insightful observation is that a major obstacle to the development of alternatives is a lack of an open-minded attitude by the various stakeholders. This grower stated that a lack of consideration for other points of view creates an atmosphere of intolerance that perpetuates the current situation. Only one of the non-growers thought that there are no constraints to the development of alternatives to carbaryl. Others agree that the level of funding and technical or research knowledge was too low, due to the economics of the industry. Two non-growers agree that the regulatory agencies constrain the development of alternatives through their process of regulation, permitting, and general inertia. Public opinion and government scrutiny of alternative methods was mentioned, as was the domination of the pesticide application procedure by the oyster industry.

IV. Environmental Impacts Of Shrimp Management

Only four growers responded to questions regarding the short and long term benefits and negative impacts of using carbaryl for the control of burrowing shrimp. The short term benefits reported were the immediate mortality of shrimp in the treated areas, which in turn limits oyster loss. Growers listed as a benefit that the application method was a good one to treat large areas. They also indicated that carbaryl application allowes for the growth of eelgrass. Several non-growers noted that in the short term the carbaryl application kills shrimp, allowing the substrate to harden, which benefits the oyster industry. Only one thought that there are no short term benefits.

Over the long term, growers indicated that carbaryl treatment boosts the yield of oysters in the estuarine beds. This keeps the industry economically healthy and saves jobs and related employment in the industry. At least some growers believe that carbaryl treatment reduces the shrimp abundance and distribution in the bay.

Non-growers agree that the industry benefits in the long term through the use of carbaryl, with some noting that water quality benefits both from the presence of the growers, as well as through the filtering of the oysters. Several noted that the decrease in the abundance of shrimp is good for the ecosystem, through enhanced species diversity and lower sediment movement rates, as well as the maintenance of functional habitat for non-shrimp species. Several thought there are no benefits to carbaryl use, or declined to answer.

Two of the four responding growers reported negative impacts resulting from carbaryl treatment. Only one short term aspect was noted, the toxic effect on non-target animals and oyster beds. One grower indicated uncertainty regarding whether the chemical could bind to the clay soils of the estuarine bottom, or whether there was negative effects on the oysters or water quality over the long term. One grower listed a loss of species diversity as a long term negative impact from spraying. The other two growers who responded to this question indicated that there were no negative short or long term impacts from the spraying of carbaryl.

Non-growers are more vocal regarding the negative aspects of carbaryl use. Their primary concern is the non-target species mortality, especially the elimination of crustaceans. Water quality may be impacted in the short term, a possible human health issue, although one noted that a general fear of the chemicals in the water was exacerbated by the treatment. Non-growers expressed some uncertainty as to the long term effects of carbaryl use. The negative public perception of chemical use may harm the industry, either directly or through a decreased market image of the oyster product. Long term effects may include the polarization of the local community as people line up on opposing sides of this fractious issue. One non-grower thought the short term impact is insignificant, while another argued that the sprayable acreage allowed is too small, limiting the effectiveness of shrimp control. Another noted that this type of management involving pesticides in an aquatic setting would not be allowed in other similar estuarine systems.

Growers listed several impacts related to areas of high shrimp abundance in the bay. One grower thought that high densities of shrimp only negatively affected oysters by reducing the amount of food available, however the general consensus was a lower overall level of estuarine biodiversity. Several described a condition of a "shrimp monoculture" that created a "marine desert" condition in the benthic community. Among the negative impacts are a reduction in benthic habitat for eelgrass, other benthic plants, shellfish including cockles, scallops and several types of clams, burrowing worms, waterfowl such as Brandt's Geese and pelicans, and fish. Some growers indicated that the high densities of shrimp has altered the estuarine ecosystem in general, lowering its overall productivity.

More than half of the non-growers agreed that high shrimp densities lowers the level of ecological diversity through the reduction of habitat suitable for the above mentioned species. High rates of sediment suspension may decrease the photic levels necessary for benthic plant growth. Two non-growers think that high shrimp densities have a positive ecological effect, either by providing a positive effect on water quality or by providing food to their predators. These same individuals were adamant that the shrimp are a natural component in the estuarine ecosystem and that defining environmental quality in relation to the abundance of specific indigenous species was not possible. They maintain that managers should not be attempting to regulate the components of a highly complex environmental system.

Growers indicated that high shrimp densities benefited some community species, especially those that are shrimp predators. These include finfish such as sturgeon, some salmonids and perch, as well as gulls. Two growers thought there are no benefits to natural resources from high shrimp densities, another thought baitfishermen who harvest the shrimp derive some benefit, and another believes eelgrass receive some benefit from the shrimp - contradicting at least six other growers. Non-growers noted that in addition to the species listed by growers, grey whale, other finfish species such as trout and anchovy, as well as crabs benefit from high shrimp densities.

The survey asked growers whether the impacts of both species of shrimp were equal, repeating a question asked earlier in section II, Managing Burrowing Shrimp. However, the answers were not exactly identical, perhaps indicating some level of uncertainty in the growers' minds. Overall, the majority thought that the ghost shrimp provides more detrimental impacts, although two growers thought the impacts from the two species are the same, and two were unclear which has the greater impact. More than half of the non-growers indicated uncertainty or declined to answer. Those that did indicated that ghost shrimp are the most detrimental, but noted that while these shrimp destabilize the sediment most, they think the mud shrimp provide the most competition for food in the estuary.

Growers indicated that the primary estuarine environmental benefit associated with the oyster farming industry is the control of burrowing shrimp. This may be because many of them feel benthic habitat is created for other species with the control of the shrimp. The increase in biodiversity includes invertebrates such as crabs, shellfish and sponges, as well as eels, shiner and other finfish. Growers also regard themselves as an important safeguard for water quality in the estuary. Several noted that growers function as a "watchdog" for incompatible estuarine uses, or nearby land uses, that might serve to degrade the water quality. In addition, growers keep the notion of water quality a high priority, sometimes filing lawsuits against other parties. One grower suggested that the oysters themselves improve water quality through their action as filters of the bay waters. While two growers thought that oyster growing creates conditions benefiting the growth of eelgrass, another thought that oyster growing reduces eelgrass growth. This grower indicated that this reduction is a good thing as eelgrass reduces water flow and could lead to stagnant water conditions. One grower noted that the oyster industry provides state revenue and employment, although it is difficult to construe this as an environmental impact.

The dominant environmental benefit from oyster farming noted by non-growers is the increase in biodiversity through the enhancement of habitat for benthic plants and animals. Non-growers also noted the promotion and support of water quality by the growers through political and social pressure, as well as through the physical aspects of the oysters filtering water. One non-grower raised a particularly salient point in this regard: the presence of oyster growers and their crop is on the whole a positive aspect, however the disturbance involved in the culture methods, especially bottom culture, is usually bad.

Almost half of the growers responded that there were no negative environmental impacts from oyster farming. This question was asked effectively twice; some growers took this opportunity to comment on oyster methods that they did not personally use but which they thought causes negative impacts. The main negative impact for ground culture methods is the effect of dredging on the benthic habitat and associated species. This is mostly due to the turbidity caused by disruption of the sediment, but also to direct mechanical stress and mortality. There are two types of negative impacts associated with off-bottom culture methods, plastic and other debris such as ropes and mesh bags, and changes in the water flow as a result of the structures in the water. Changing the flow of the water may result in sedimentation deposits around the structures, which several growers noted is a temporary effect, reversed when the structures are removed. One grower noted off-bottom methods may deplete food levels in the water column. Another noted the pollution caused by outboard motors on the growers' boats.

Non-growers echoed the criticism of dredging and other mechanical disturbance on the substrate, especially its effect on eelgrass and the resuspension of sediments. As carbaryl remains integral to some growers' operations the non-target mortality was listed by some non-growers. Marine debris from off-bottom culture was noted as was the aesthetics of the growing structures. One person noted that since the oyster is an exotic component of the ecosystem, its presence is thus a negative aspect. Additionally, the monoculture of oysters may displace other benthic species that would naturally occur. Two non-growers could find no major negative impacts from oyster farming operations. The non-growers are fairly united in the belief that the greatest negative impact of oyster farming is the disruption of the bottom substrate by mechanical operations, but several questioned whether this was worse than the effect higher shrimp densities might cause. Debris from off-bottom operations was also noted, possibly causing animal entanglement, and causing general ugliness. Others noted the farmers' impact on eelgrass through dredging or mowing, and questioned whether farmers' impacts in this regard might actually promote shrimp infestation.

Three growers thought that no changes are needed to improve estuarine environmental impacts, two did not know of any helpful changes and two did not answer. One off-bottom grower suggested reducing the acreage of ground culture to lower the amount of impact associated with dredging. One bottom grower suggested a reduction in long-line operations to curb associated debris problems, while a long-liner thought this could be accomplished through better maintenance of equipment. Another suggested increasing the acreage of ground production, noting that this would increase the provision of crab habitat from oyster beds. One grower suggested eliminating the use of carbaryl.

Non-growers would like to see the overall intensity of disturbance decreased, as three requested a decrease in dredging or other manipulation of the substrate, and another a decrease in eelgrass mowing. Two suggested more off-bottom culture efforts, including long lining, rack and bag, and the previously mentioned platforms above the bottom. Two suggested a reduction in carbaryl application, and another would decrease marine debris through the use of biodegradable seed bags. Industry expansion is viewed as favorable by one respondent, along with a wish that the industry maintain its consciousness as environmental stewards.

Regarding the efforts of the local community, state or federal government to help farmers reduce negative impacts to the estuarine environment, almost half the growers thought these groups have no role to play, aside from possibly forcing the farmers out, according to one. Two growers suggested more rigorous control of sewage inputs from local development, either through new sewage treatment facilities or enforcement of existing regulations. One suggested the development of alternative shrimp control and another thought new regulations could provide additional protection for shrimp predators in the estuary. One grower thought regulatory agencies should permit an expansion of suspended culture in new areas.

Several of the non-growers thought that these groups could play a progressive role in the development of alternatives to growers' current operating methods. Alternative cultural methods, or research, could be subsidized, as could the development of better application methods and other means of pest control. Other research could focus on shrimp recruitment or reproductive dynamics. Regulatory agencies should maintain flexibility in dealing with the growers, and concentrate on monitoring the negative impacts of septic pollution and development. Although one non-grower thought that the continued use of carbaryl should be allowed, another suggested no expansion of the current allowable acreage. Among the non-growers there was some consensus that growers are not the source of problems in the estuaries, rather much blame could be laid on the regulatory agencies.

The growers were considerably more vocal on how these same groups could aid the efforts of farmers in burrowing shrimp control. There were several responses relating to the regulation of carbaryl spraying. Some growers want the agencies to maintain the permitting process, because of the legitimacy this gives to there shrimp control activities. Several offered suggestions to improve the spray permitting process including relaxing or expanding both area allotments and the rate of application, or allow growers more flexibility in general. One suggested that the permitting agencies base the spray allotments on scientific information (i.e. based on need to control shrimp). This individual maintained that allotments are based on the acreage requested to be sprayed, meaning that a grower who asked for a larger spray area got a higher percentage of his request than if he requested to spray a small area. Growers also requested that they be given more flexibility on the seasonal timing of the spray, based on the life cycles of the shrimp, rather than to reduce non-target effects.

One grower suggested that the state could spray currently infested areas at state expense to allow for the expansion of farmable acreage. This person reported that the state is not a good neighbor in the sense that state lands adjacent to some farmed areas are infested and remained untreated. However, there is also some sentiment for limited government help, as some growers responded that the government and local groups should "stay out of our way" to aid the growers.

Some growers thought that a way to help their efforts is for government and local groups to adjust their attitudes in favor of the oyster industry and growers. Agencies and the public, according to this view, should be more supportive of the growers and the use of chemicals, and increase public awareness and education regarding the concerns of the health of the industry, and the safety of the current spraying activities.

Other roles of the government agencies include more research and development into alternative shrimp control strategies, including new regulations protecting biological predators of burrowing shrimp. One suggestion is to modify the marine mammal protection act to reduce the abundance of seals which prey on finfish predators of shrimp. One grower also suggested conducting an environmental impact study relating to growers' activities in the estuaries. Another endorsed the implementation of a true and comprehensive integrated pest management plan for the control of shrimp.

Non-growers generally agree that an important role for local and governmental groups is the financial support for applied research into IPM measures, alternative culturing methods, and other basic biological research such as shrimp predation. Regulatory agencies and the public should acknowledge the role of growers in the protection and promotion of estuarine water quality, according to some non-growers. Another indicated that the agencies should continue to maintain a regulatory basis for continued carbaryl use, and one individual voiced support for the encouragement of shrimp harvesting.

Appendix C.

A Benefit-Cost Approach for Evaluating New Control Methods

BENEFIT-COST ANALYSIS FOR EVALUATING NEW CONTROL METHODS

Benefit-cost analysis provides an objective means for comparing new control methods with those currently in use. In this section, we provide general guidelines for conducting benefit-cost analyses. Before developing a more specific benefit-cost model, oyster growers and resource agencies will need to agree on the major factors to be weighed in the analysis, for example, the yield of oysters and impacts to environmental and human resources.

I. Background: Decision-making in pest management, like in other economic problems, involves allocating scarce resources to meet human needs. Initially, there is the choice of whether, when, and how to attempt to manage pests with minimum labor and capital. Other resources may also be scarce, such as an uncontaminated environment or information on the extent of pest infestation. These issues will affect particular choices.

A number or authors have used traditional benefit-cost modeling in an attempt to evaluate the economics (i.e., the efficient allocation of resources) of specific control programs (John et al. 1987; Grundy 1989; Greer and Sheppard 1990; Radke 1993), and much can be learned from these examples. However, no studies have been conducted to date that consider the costs and benefits of burrowing shrimp management programs or that assess the comparative economic efficiency of alternative control practices.

2. The Basic Model: Benefit-cost analysis is a method that compares ex ante the present values of all social benefits and all opportunity costs of using resources. It is a means of determining the economic efficiency of management and regulatory actions. A project or action adds to the welfare of society and is economically efficient if its net present value (present value benefits minus present value costs) is greater than zero.

Benefit-cost analysis is the major tool for the economic evaluation of public programs in natural resource management. It is an integral part of the Environmental Impact Analysis process, meant to evaluate the impacts of public and private developments on environmental resources. As the name implies, a benefit-cost analysis involves measuring, adding up, and comparing all the benefits and all the costs of a particular public project or program.

There are essentially four steps in a benefit-cost analysis:

1. Specify clearly the project or program.

2. Describe quantitatively the inputs and outputs of the program.

3. Estimate the social costs and benefits of inputs and outputs.

4. Compare benefits and costs.

In a benefit-cost analysis, the first step is to decide on the perspective from which the study is to be done. Benefit-cost analysis is typically a tool used in public analysis, but there are actually many publics. For example, oyster growers might have the perspective that the sole consideration of the benefit-cost analysis for a control tactic is the yield of the crop; an environmental regulator might have a different perspective, such as impacts to non-target species. It is possible to include more than one perspective in a benefit-cost study by conducting separate benefit-cost evaluations for each goal (i.e., oyster yield and non-target toxicity) and comparing the results for each goal. If the goals are completely different, then some independent criteria should be established prior to starting the analyses as to how to weigh the relative importance of each goal. The first step also specifies all the main elements of the project or program: location, timing, groups involved, connections with other programs, etc.

Once the basic project or program has been defined,the next step is to determine the relevant flows of inputs and outputs. For example, assuming the scenario of conducting an analysis of a control tactic from the perspective of increasing yield to oysters, inputs could include cost of the control method, cost of damage by the shrimp, efficacy of the control method (number of shrimp eliminated per unit time), frequency of application of the control method, relationship between density of shrimp and loss to oyster yield, cost of sampling shrimp, and other considerations. Outputs could include changes in shrimp density, changes in oyster yield, and changes to other economic aspects of oyster growing. It is in this step that importance of time must be recognized. The job of specifying inputs and outputs involves predictions of future events, often quite remote in time. This puts a premium on having a good understanding of factors such as population growth rate of the shrimp, the rate of growth of the oysters, costs of production, and market value of the crop.

The next step is to put values on input and output flows, that is, to measure costs and benefits. This can be done in any units desired, but normally benefits and costs are measured in monetary terms. A number of nonmarket techniques currently employed by environmental economists can also be considered for assessing those elements of a program not as easily measured in monetary terms.

Finally, benefits and costs are compared. This can be done in several ways. One way is to subtract the total costs from total benefits to get "net benefits." Another criterion is the benefit-cost ratio, which measures the ratio between the cost of a project versus the benefits derived form such a project. Any benefit-cost ratio less than 1.00 means that it costs more to carry out the program than is derived from it. In private business, any operation with a ratio less than 1 would not stay in business very long. For public investments, any benefit-cost ratio less than 1 means that the benefits (if properly evaluated) are not enough to cover the costs of carrying out such a program.

3. Assumptions Underlying the Benefit-Cost Analysis: Assumptions important to the burrowing shrimp benefit-cost analysis include the time frame of the analysis, the varying costs of a program, factors of uncertainty, and cost to the environment.

Time of Evaluation: Unlike some control programs (Radke 1993), the burrowing shrimp control program has been financed by the oyster growers themselves over the last 30 years. In terms of a time frame for the benefit-cost analysis, we can ask one of two questions. First, are potential control strategies financed by the growers greater than the costs to the growers (and to the public in the case of environmental costs)? Or, in the event of a publicly sponsored program, do the benefits of an investment in a plan outweigh the public and private costs at this point in time, taking into account that some benefits and some costs may not accrue until some time in the future?

Cost of the Control Program: If the control plan is financed by an oyster grower, the specifics of that grower's business must be identified. For example, are there expectations of decreases in future costs to produce the crop (such as plans to purchase new equipment or to grow oysters on different beds), are there expectations of changes in the frequency of applying a control tactic (i.e., does some other practice reduce the rate of shrimp population growth, thus reducing the necessity of application), or are there other external factors that can reduce or increase the need for management? In addition, it must be identified whether the burrowing shrimp control program is a single program or part of some larger total program addressing other pests affecting the oyster industry.

Uncertainty and Control: Assumptions about the effectiveness of control methods are based on surveys and on observations. In most cases, such evaluations must be used to make predictions about future events. There are many uncertainties involved in the use of most alternative control measures. Probabilities of success and failures must, therefore, be included in the analysis. Other considerations, such as probably rates of burrowing shrimp spreading into other areas with and without any control programs, must also be included. Such probabilities can be based on statistical models, experience, or on expert opinions (Radke 1993). To properly evaluate the program, the likelihood of success of the program must then be taken into account; i.e., potential benefits of a program must be weighted in in ralationship to the probability of them being attained. A decision-theory approach can be a useful method for accounting for the uncertainties involved in a control program (Grundy 1989, pp. 31-33).

Environmental Costs: As indicated below, there are both market and non-market costs and benefits associated with the control of burrowing shrimp. One example of the non-market environmental value of the control of burrowing shrimp is potential improvements to critical eelgrass habitats. A value of many alternative control measures might be the decreased use and associated costs of pesticides, along with reduced environmental risks. Clearly, market benefits and costs are more readily adaptable to a benefit cost framework. However, unlike goods and services traded in markets, the benefits of many natural resource and environmental amenities are not always measurable in monetary terms. Economists have non-market measurement techniques available to estimate these costs (or lost benefits). A number of studies addressing the economic evaluation of pest control have used non-market measurement techniques in the estimation of the benefits of the control program. Greer and Sheppard (1990) use the contingent valuation method to assess the benefits of the biological control of *Clematis Vitalba*. Reiling et al. (1988) also use the contingent valuation method to assess the value of biological agents to control black flies. Resources may limit the extent to which these costs can be estimated, however.

4. Net Economic Benefits: The following factors must be considered in calculating or modeling net economic benefits and losses:

Costs of Burrowing Shrimp Management: As part of an integrated program to address the damage caused by burrowing shrimp, the costs associated with controlling burrowing shrimp must be identified. Three main areas of costs have been identified:

1) Loss of oyster yield (e.g., number of bushels lost x conversion factor x price/gal.)
2) The cost of spraying pesticides
3) Other environmental losses (e.g., loss of eelgrass beds or oyster shell habitat for Dungeness crabs)

Effectiveness of the Control Method: Although effectiveness of an alternative control measure can be based on a number of variables, Radke (1993) suggests that observed reduction in population is probably the most logical criterion to use. Estimates may range from 0% to 100%.

Benefits of Reduced Control Costs: This entails the estimation of the costs of past means of control (e.g., spraying with Sevin). By multiplying the effectiveness of the control measure in question by the alternative control cost, the benefits of reduced control costs can be estimated.

Estimated Value of Yield Loss Caused by Burrowing Shrimp: The estimated loss of the annual value of oyster yield multiplied by the effectiveness of the control measure in question results in an estimate of benefits of control in terms of losses avoided as a result of using the control measure. Total estimated benefits of a control measure are thus equal to the sum of the gain from reduced control costs plus the gain from avoided losses as a result of the control measure.

Net Annual Benefits of the Control Program: The net annual benefits of the control program in question is measured as the difference between the annual cost of the control program and the net annual benefit of the program.

Present Value of Net Benefits: The net present value is the worth of the incremental net benefit stream discounted at an appropriate interest or discount rate. Often, a range of discount rates are employed in a sensitivity analysis. Discount rates of 3% to 10% are recommended to estimate the present value of the stream of net benefits over a specified period of time (i.e., the life of the program). The cumulative net present value is then estimated as the sum of this stream of net values.

Benefit-Cost Ratio of Various Control Measures: The benefit-cost ratio is the present worth of the benefits divided by the present worth of the costs. Both benefit and cost streams are discounted at an appropriate discount rate. Then the ratio of the present worth of the benefits and the present worth of the costs is calculated.

Appendix D.

Selection and Field Testing of Other Pesticides

The Willapa-Grays Harbor Oyster Growers Association and the Washington State Commission on Pesticide Registration funded a project to screen less-toxic alternatives for control of burrowing shrimp in oyster beds. The project, consisting of two sets of trials, began in April 1996 and was completed in September 1996. The objective of the first trial was to determine whether selected reduced-risk compounds were capable of controlling burrowing shrimp. The objective of the second trial was to collect data to aid development of a cost-effective use pattern for the control of burrowing shrimp.

The first trial was designed to measure the relative effectiveness of four compounds at killing burrowing shrimp. These compounds included two new generation neurotoxins, abamectin (Agri-Mek) and imidacloprid (Provado), a chitin inhibitor, diflubenzuron (Dimilin), and a juvenile hormone mimic, fenoxycarb (Comply), which were selected for trial based on the criteria outlined in the previous section. The four compounds were each applied at three rates. Including a control, the experiment consisted of 13 treatments. Each treatment was randomly assigned to plots and replicated three times, for a total of 36 plots. Three additional plots were included as controls. The plots, measuring 100 square feet, were arrayed in more or less a straight line parallel to the incoming tide. The compounds were applied on May 6, 1996. To quantify impacts to burrowing shrimp, researchers counted burrows one day prior to pesticide application (initial density) and 15 days, 30 days, and approximately 60 days after application. Burrow counts were obtained by counting the number of burrow openings in a 0.25-m^2 quadrat at two locations within each treatment plot.

Based on samples taken by Dr. Dumbauld, the burrowing shrimp population consisted of ghost shrimp only. Burrow counts on control plots did not change over time, suggesting that shrimp populations remained stable during the experiment. Results of the first field trial are presented in Table D.1. Diflubenzuron and fenoxycarb had no negative influence on shrimp populations. Abamectin applied at the low- and medium-application rate also had no negative impacts on shrimp populations. Abamectin reduced the number of burrows from 7.7 b/m^2 to 0.2 b/m^2 (38.5-fold reduction) at the high-application rate. Imidacloprid had no negative influence on shrimp populations at the low-application rates. Imidacloprid reduced the number of burrows from 14.8b/m^2 to 1.8b/m^2 (8- fold reduction) and from 12.8b/m^2 to 0.3/m^2 (42.6-fold reduction) at the medium- and high-application rates, respectively. This information suggests that applications of abamectin and imidacloprid are capable of reducing ghost shrimp populations. The three treatments that reduced burrow densities also caused a noticeable stabilization of the tidal ground. Furthermore, deposition of organic matter (evident as an orange film on the sediment surface) occurred on shrimp-defaunated plots in contrast to plots with uncontrolled shrimp populations. No visual evidence of negative impacts to non-target species were observed immediately post application, or at the 15-day or 30-day assessments.

Based on results of the first trial, a second field experiment was conducted to determine the efficacy of imidacloprid and abamectin relative to carbaryl for control of burrowing shrimp. The goal of the second experiment was to establish a feasible use pattern using the lowest effective application rate of imidacloprid and abamectin. This experiment was conducted near the western tip of the North Beach Peninsula near Stackpole, north of Oysterville, Washington. The second set of applications was similar to those used in the first experiment, with major differences being the exclusion of diflubenzuron and fenoxycarb and the inclusion of carbaryl for comparative purposes. Rates tested were lower than those used in the previous trial, the number of replications was increased, plot size was expanded, and the influence of carrier volume on efficacy was examined. As in the previous trial, ghost shrimp was the dominant burrowing shrimp species on the experimental plots. Two other pesticides were each applied at three rates: abamectin at 0.06, 0.1, and 0.2 pounds active ingredient per acre; and imidacloprid at 0.25, 0.5, and 1.0 pounds active ingredient per acre. Each application was delivered at two different carrier volumes: 10 and 50 gallons of water per acre. The 10-gallon applications approximated aerial application, whereas 50-gallon applications approximated possible commercial ground application. Carbaryl was applied at two rates: 4 and 8 pounds of active ingredient per acre and at two volumes: 10 and 50 gallons of carrier per acre. Including a control, there were a total of 17 treatments. Each treatment was replicated four times, for a total of 68 plots. Each plot measured 20 ft by 20 ft, plots were separated by ≥20 ft, and the plots were arrayed approximately parallel to the incoming tide. This arrangement was designed to minimize drift of chemicals from one plot to another. No plot was within 20 feet of a channel or other body of water. Plots were established on July 29, 1996, and applications occurred on July 30 and 31. Four replicate burrow counts (using 0.25-m^2 quadrats) were made on each plot one day before the first set of applications, and approximately 30 and 60 days after application.

Water samples for carbaryl and imidacloprid were collected at high tide approximately 5 hours following immersion of plots by the incoming tide on the day of pesticide application. Sediment samples for carbaryl and imidacloprid were collected at 24 hours after application. Chemical analyses were conducted at the Washington State University Food and Environmental Quality Laboratory, Richland, Washington. Abamectin was not included in the residue analyses because of an inability to locate a lab with analytical capability to measure the compound.

The impact results from the second trial are presented in Table D.2. On all treatment plots, burrow counts after pesticide application declined precipitously from the pre-application counts. However, the number of burrows did not vary among treatments, regardless of which pesticide was applied, the application rate, or the volume of application. Burrow counts on very few of the treated plots were significantly different from those on the control plots. This all suggests that a strong external factor caused burrowing shrimp populations to decrease on all of the experimental plots. A possible explanation for these results may be the proximity of the experimental area to an oyster bed that had been treated with carbaryl approximately 4 weeks prior to the study. This bed, just south of the experimental site, was treated with carbaryl during the first week of July 1996. The closest experimental plots were approximately 350 ft from any area previously treated with carbaryl. Tufts (1989) reported reduction in burrow counts up to 300 ft from areas treated with carbaryl.

Additional insight may be obtained from examination of environmental monitoring data (Table D.3). Carbaryl residues were detected in all samples of water, including the control sample that was taken from water that had not yet interacted with carbaryl-treated experimental plots. Carbaryl residues were detected in sediment samples at levels higher than in the water samples. A significant amount of carbaryl was detected within a plot that had been treated with carbaryl 24 hours earlier. It is interesting to note that, in an earlier study by WSDA (1988), carbaryl was also found in control samples at somewhat similar concentrations; however, contamination of samples was suggested as a cause. The residue concentration is consistent with data reported previously by WDF/WDOE (1992).

Imidacloprid residues were detected in all samples of water, including the field-collected control sample. Concentrations in several samples, including the control sample, were at or below the limit of analytical detection; the accuracy of these measurements is thus limited to the detection limit. Although imidacloprid was detected in three sediment samples, the only sample in which the concentration was above the detection limit was from the experimental plot that was treated with imidacloprid. Based on the limited analytical chemistry, it would appear that carbaryl was present throughout the study area and moved onto the experimental plots. Imidacloprid was present in analytically low levels only in the test area after application. In all cases, the concentrations of carbaryl and imidacloprid were low outside of the plots, both in water and sediment samples.

In the first trial, Schreiber and Wildman found that abamectin and imidacloprid were capable of controlling burrowing shrimp. However, results from the second trial were inconclusive. Chemistry data and the proximity of recently treated oyster beds suggested that carbaryl from an outside source entered the second-trial study area, contaminated the water or sediment, caused a wide-spread reduction in burrowing shrimp populations throughout the study site, and thereby interfered with the field trial. Thus, the cost-effective application rate and volume of abamectin and imidacloprid remain uncertain.

Table D.1. Results of the First Field Trial of Alternative Pesticides Showing Burrow Counts per m^2 Before and After Treatment of Oyster Beds with Four Pesticides at Several Different Application Rates

Compound	Rate (lb/ac)	Pretreatment 6 May Ave b/0.25 m^2	15-day post treatm. 22 May Ave b/0.25 m^2	30-day post treatm. 6 June Ave b/0.25 m^2
Abamectin	0.02	15.3	21.7	21.5
	0.1	12.0	9.0	9.0
	0.5	7.7	2.7	0.2
Imidacloprid	0.1	13.7	11.2	12.8
	0.5	14.8	7.0	1.8
	2	12.8	0.3	0.3
Diflubenzuron	0.25	10.5	11.7	12.0
	1	9.8	10.2	11.2
	5	15.2	14.3	13.0
Fenoxycarb	0.2	15.5	17.7	15.7
	1	13.0	13.0	10.3
	5	15.7	9.3	16.7
Control			17.0	17.8

*Burrow counts are a mean of three replicate 0.25 m^2 quadrat counts per treatment; each quadrat was double counted for precision.

Table D.2. Results of the Second Field Trial of Alternative Pesticides Showing Burrow Counts per m^2 Before and After Treatment of Oyster Beds with Three Pesticides at Several Different Application Rates

Compound	Rate (lb/ac)	Pretreatment Ave b/0.25 m^2	30-day post treatm. Ave b/0.25 m^2	60-day post treatm. Ave b/0.25 m^2
Carbaryl	8 @ 50gal	8.2	1.5	0.4
	8 @ 10gal	8.2	0.5	0.1
	4 @ 50gal	9.6	0.8	0.4
	4 @ 10gal	9.4	1.6	0.9
Abamectin	0.2 @ 50 gal	7.4	0.5	0.6
	0.2 @ 10 gal	8.2	0.6	0.4
	0.1 @ 50 gal	12.3	1.1	0.4
	0.1 @ 10 gal	12.2	1.7	0.6
	0.06 @ 50 gal	10.5	1.8	1.5
	0.06 @ 10 gal	8.8	2.1	1.4
Imidacloprid	1.0 @ 50 gal	8.5	2.0	0.7
	1.0 @ 10 gal	13.5	1.8	1.6
	0.5 @ 50 gal	11.9	1.4	1.0
	0.5 @ 10 gal	8.1	1.7	1.7
	0.25 @ 50 gal	7.8	2.9	2.7
	0.25 @ 10 gal	12.1	6.9	2.6
Control	0	11.4	2.7	1.0

*Burrow counts are a mean of four 0.25 m^2 counts per treatment (each counted four times for precision)

Table D.3. Pesticides Concentrations 24-h after Application During the Second Trial

Distance from site of application (ft)	Carbaryl (ppm)		Imidacloprid (ppm)	
	Water	Sediment	Water	Sediment
Control (background)	0.0092	na	<0.0005*	
0 (test plot)	0.0025	0.332	<0.0005	0.111
50	0.0077	0.018	0.0012	<0.003
150	0.0044	0.001**	<0.0005	0.002**
350	0.0029	0.027	<0.0005	0.004**
750	0.0039	0.021	<0.0005	<0.003
Detection Limit	0.0001	0.004	0.0005	0.003

* Residues at or lower than the limit of detection are marked with a < sign.

** The accuracy of values below or close to detection limits should not be considered reliable.