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THE OLYMPIA OYSTER, *OSTREA LURIDA* CARPENTER 1864 ALONG THE WEST COAST OF NORTH AMERICA

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The Olympia oyster, *Ostrea lurida*,† is the only native oyster species on the west coast of the United States and Canada. Once an abundant estuarine organism, its historic range (Fig. 1) was from Baja, California, Mexico, to Sitka, Alaska (Dall, 1914); however, significant declines and, in some areas, near extirpation of the Olympia oyster have occurred throughout its range within the past two centuries. Overharvesting, pollution, sedimentation, urbanization of estuarine areas, predation by nonnative species, and lack of sufficient attachment substrate (cultch material) have all led to the declines (Fig. 2).

In recent years, scientists and restoration practitioners have sought to know more about the Olympia oyster and to restore it in areas where it previously existed, or where only remnant populations are now found. To date, more than $1million has been invested in restoration efforts of *O. lurida* in west coast states (NOAA Restoration Center data). Because of the increase in restoration activities and the relative paucity of information and lack of research conducted on this species (including knowledge about genetic variation), the NOAA Restoration Center, in conjunction with other sponsors, convened two West Coast Native Oyster Restoration Workshops. The first, in 2006, was held in San Rafael, California, and the second in 2007 in Shelton, WA (NOAA Restoration Center 2007, 2008). The workshops brought together scientists from academia and resource agencies, restoration practitioners, resource managers, oyster growers, and representatives of nonprofit organizations to exchange information about restoration efforts, monitoring, and research in an effort to improve restoration of the species. Attendees also discussed short- and long-term goals; priorities for future research, restoration, and monitoring; and addressing administrative procedures in their states (e.g., permitting processes for restoration activities).

As planning for the second workshop progressed, it became apparent that, in addition to the workshop proceedings (NOAA Restoration Center 2007, 2008), there was an unprecedented opportunity to create a dedicated volume summarizing current information regarding the Olympia oyster. The current volume includes some of the papers presented during the workshops and additional papers from researchers and restoration scientists unable to attend the workshops. A call for manuscripts resulted in submission of over a dozen papers. In addition to personal reviews, each manuscript was reviewed by at least two experts in the field. I thank the referees and the authors for their contributions to this special volume, which substantially increases the number of refereed articles concerning *Ostrea lurida* and advances considerably our knowledge of the species.

Many of the papers in this volume contain recurring themes (e.g., history and status of the Olympia oyster in different localities), results of restoration projects, and studies on ecological factors; others contain unique and interesting approaches to certain aspects of life history such as larval identification, oyster genetics, and larval dispersal (e.g., Wight et al. Polson et al. and Zacherl et al. 2009). Several deal with the potential negative effects of well-intended restoration efforts, and include cautionary notes about repeating mistakes made in restoration efforts with the Eastern oyster, *Crassostrea virginica*, along the Gulf and east coasts of the United States (e.g., Brumbaugh & Coen, Camara & Vadopalas, 2009). The authors also offer suggestions for improving techniques or avoiding adverse impacts of restoration activities.

The taxonomic status of the Olympia oyster has been in doubt for several years since Harry (1985) synonymized *Ostrea lurida* Carpenter 1864 with *Ostrea conchaphila* Carpenter 1857. The latter taxon has since been adopted by the American Fisheries Society and subsequently applied to the Olympia oyster by some scientists. In addition, until recently there were few genetic studies to clearly delineate the two species. Polson et al. (2009) used a molecular approach to test the single versus two-species hypothesis. Their results provide very strong evidence that *O. lurida* and *O. conchaphila* are, in fact, two distinct species, with *Ostrea lurida* Carpenter 1864 inhabiting the west coast from approximately central Baja California northward, and *O. conchaphila* from Sinaloa, Mexico southward to Panama. Thus I use *Ostrea lurida* and Olympia oyster as the scientific and common names in this introduction to reflect these new findings. I also agree with Baker (1995) that *Ostrea lurida* should be retained as the scientific name for the Olympia oyster for several other reasons, namely: (1) Harry's determination was based on shell and anatomical characteristics, not molecular evidence; (2) most of the scientific papers and fishery publications about the species refer to it as *Ostrea lurida*, and very few as *Ostrea (Ostreola) conchaphila*; and, following from this usage, (3) conformity with provisions of the International Code of Zoological Nomenclature regarding suppression of unused senior synonyms dictates that *Ostrea lurida* should be used.

Using several molecular markers, Polson et al. (2009) compared samples of Olympia oysters from Sinaloa, Mexico (near the type locality of *Ostrea conchaphila* Carpenter 1857), Willapa Bay, WA (the type locality of *Ostrea lurida* Carpenter 1864), and from several other intermediate locations. The authors state that the Sinaloa oysters represent the true *O. conchaphila* and that the two taxa are distinct, separated

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†The taxonomy of the Olympia oyster has been in dispute since Harry (1985) proposed synonymy of *Ostrea lurida* Carpenter 1864 and *Ostrea conchaphila* Carpenter 1857. Polson et al. 2009 provide molecular evidence that the Olympia oyster refers to the nominal species, *Ostrea lurida* Carpenter 1864. In view of their genetic data, and for consistency, the original taxon, *Ostrea lurida*, is used throughout this volume to refer to the Olympia oyster, which is distributed from approximately Baja California (Mexico) to southeast Alaska.

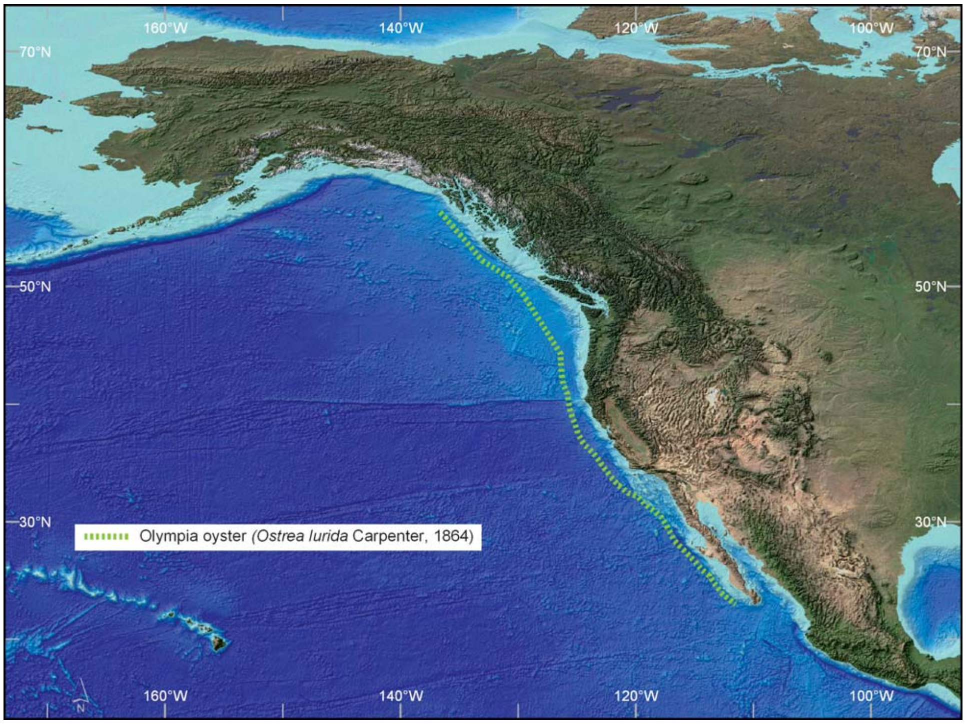

Figure 1. Historic range of the Olympia oyster, *Ostrea lurida* Carpenter 1864. (Map courtesy of Marti McGuire, NOAA Restoration Center).

by geography and climate. The researchers also used several potentially diagnostic shell and soft-tissue morphological characters (e.g., chomata, shell color and sculpture, mantle tentacles) to identify samples collected from Mexico, independent of molecular results, then performed a posthoc comparison against molecular outcomes. They found no shell or anatomical characters that could be used reliably to distinguish between *O. conchaphila* and *O. lurida*; however, the authors state that, ''despite the present lack of any morphological diagnostic differences for separating these nominal species, the molecular data are not consistent with the synonymy of the species and support reinstatement of *O. lurida* from all the localities north of central Baja California'' (Polson et al. 2009). In view of these results, other reasons stated above, and to avoid confusion, the nomer *Ostrea lurida*, as originally described by Carpenter in 1864 is used in the papers in this volume to refer to the Olympia (native) oyster from central Baja California to Sitka, Alaska.

The source, identification, and quantification of oyster larvae are often key issues in oyster cultivation as well as restoration projects. In their research, Zacherl et al. (2009) used several elements found in seawater to determine whether the shells (prodissoconchs) of *Ostrea lurida* larvae reflect elemental concentrations in seawater, whether ontogenetic changes occur in element uptake after settlement, and whether shell chemistry formed during the brooding stage changes as a result of shell thickening during the planktonic larval phase. They cultured larvae in laboratory experiments, spiked seawater with different concentrations of various elements (e.g., Ba, Pb, Ce, Ca, Cu, Sr, and Mn) approximating those found in different oceans and estuaries, and analyzed shells for several elements. Their results indicate that some elements in *O. lurida* shells do mirror the elemental concentrations in ambient water and that the chemistry of the umbo part of brooded shells remains intact through the planktonic stage. The authors suggest that the larval shells can be used as natural tags to track larval movements and identify sources of recruiting larvae.

The presence and abundance in the water column of oyster larvae, and larvae of potential pests and predators, are important factors in determining timing and placement of oyster shell for restoration projects. Wight et al. (2009) describe a molecular-based assay method (quantitative polymerase chain reaction, or qPCR) they developed to identify and quantify Olympia oyster larvae in plankton samples, with the ultimate goal of providing an efficient and cost-effective way to track larval dispersal. They amplified mitochondrial DNA regions

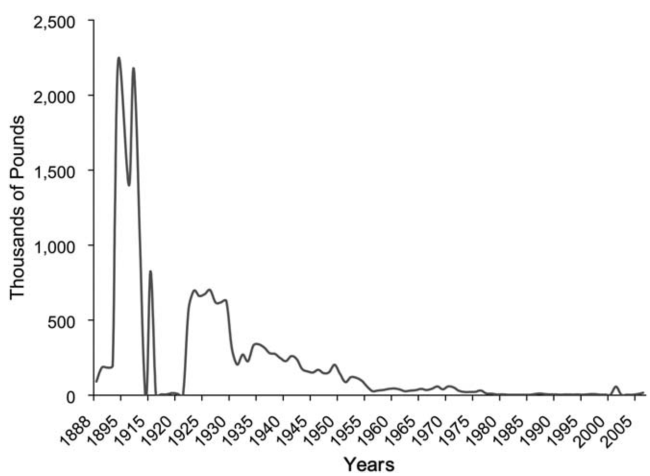

Figure 2. Olympia oyster (*Ostrea lurida* Carpenter 1864) landings (all states) from 1888 to 2006. (Data from NOAA Fisheries Statistics).

unique to *O. lurida*, then, using qPCR assays, derived standard curves that reliably estimated the number of oyster larvae for late, middle, and early stage larvae. They applied the same technique to estimate larvae of two species of burrowing shrimp, *Upogebia pugettensis* and *Neotrypaea californiensis*, which cause bioturbation and can adversely affect the growth and survival of oysters *via* sedimentation. The authors plan to conduct further studies with mixed plankton samples to test the accuracy of the assay.

Baker (1995) previously published a review of the life history, ecology, fishery, and other aspects of *Ostrea lurida*, and included a thorough annotated bibliography of existing literature about the species. Several papers in this volume also contain historic information and data regarding the Olympia oyster in the authors' specific geographic location or area (e.g., state or province). White, Ruesink, and Trimble (2009) provide background information on the history and management of the Olympia oyster in Washington State, explain why populations declined despite the establishment of protected areas, and point to mismanagement of the species as one major cause for decline, along with pollution and lack of suitable substratum for recruitment. Their paper, although it reiterates some of the topics covered in Baker's publication, differs in several ways, because it: (1) focuses on only one state in detail; (2) contains a minimal review of biological studies; (3) emphasizes political, economic, and social issues; and (4) provides a context for understanding a range of factors that may prevent overexploited marine species from recovering. The last topic is related to some other papers in this volume which examine in detail a few of the reasons that *O. lurida* has failed to recover in Washington State.

The history of the Olympia oyster in Oregon's estuaries is explored by Groth and Rumrill (2009), who gathered background information and data to document its historical and recent occurrence in Netarts, Yaquina, and Coos Bays. They describe the recovery of *O. lurida* in Coos Bay, which has extensive historic shell deposits in the bay, but nonetheless lacked any extant populations of native oysters at the time Europeans settled there. Despite previous extirpation of Olympia oysters in the bay long ago, the authors state that the oyster populations in Coos Bay are showing evidence of expansion and increasing abundance in some parts of the bay. Restoration projects are being considered to enhance recovery, but the authors caution that, as noted in Washington State efforts, availability of substratum might be a limiting factor.

In British Columbia (B.C.), Canada, Olympia oysters have suffered from some of the same problems as in other places along the United States west coast. Gillespie (2009) describes the status of *O. lurida* in British Columbia and notes that the commercial fishery for these oysters ended in the 1930s and has not resumed because of stock depletion and emphasis on the culture and harvest of nonindigenous species (primarily the Pacific oyster, *Crassostrea gigas*). He also posits that Dall's (1914) record of Olympia oysters in Sitka, Alaska is suspect and that the northernmost documented populations of Olympia oysters are found in the central north coast of British Columbia, in the Bardswell Group and at Campbell Island (between 52°10′N and 52°11′N). He further states that *O. lurida* is most common in the sounds and inlets of the west coast of Vancouver Island. Gillespie discusses some current threats to Olympia oysters in B.C. and recommends that standardized assessment techniques be developed to comport with a proposed management plan. The management plan is required as a result of the Olympia oyster being listed in 2000 as a Special Concern species by the Committee on the Status of Endangered Wildlife in Canada.

The assertion by Gillespie that the northernmost range of *O. lurida* is the northern coast of British Columbia is supported by data from Polson and Zacherl (2009), who conducted the first quantitative biogeographic survey of remnant populations of the species on the west coast. They performed searches at 24 selected sites from Baha California Sur, Mexico to Sitka, Alaska where previous studies indicated historic presence of Olympia oysters; however, they were unable to document the presence of the species at any of the Sitka Alaska sites they sampled. The authors provide information for use as a benchmark for comparing future monitoring data and also identified several sites in southern California suitable for Olympia oyster restoration efforts.

Dinnel et al. (2009) discuss results of their restoration projects in south Fidalgo Bay, WA from 2002 to 2006, constructed with the primary goal of establishing self-sustaining Olympia oyster beds. They selected the Fidalgo Bay site for several reasons: (1) historical evidence of a previously existing native oyster bed; (2) presence of potential brood stock in a nearby bay (for seed production from a close genetic stock); (3) collaboration between organizations; (4) suitable substrate and conditions for native oysters; (5) and support and authorization for the project from local government. Restoration methods included planting seed cultch as well as adding clean shell to augment settlement substrate, and the authors, with the help of volunteers, monitored survival, growth, natural recruitment, and reproductive condition of oysters in the plots over several years. The authors report excellent survival and growth at one site and provide evidence that the restoration plots planted with seed oysters are the source of native oysters that settled on cultch material in later years. Encouraged by their success in Fidalgo Bay, Dinnel et al. (2009) plan to expand restoration activities to nearby Padilla Bay.

Several papers in this volume involve laboratory and/or field experiments investigating the effects of different environmental factors on Olympia oysters, and how they might influence recovery efforts. Using field and laboratory experiments, Buhle and Ruesink (2009) examined the role of two nonnative gastropod species (Japanese drill, *Ocinebrinus inornata*, and eastern drill, *Urosalpinx cinerea*) on recovery of Olympia oysters in Willapa Bay, WA and quantified the distribution and abundance of drills in the Bay. In predation experiments, they found that both drill species preferred Pacific oysters (*C. gigas*) to native oysters of comparable sizes, and attacked smaller oysters more readily than larger ones, but that the *per capita* effect of drills (percent predation mortality per drill) on survival rates of the oysters was density-dependent (i.e., percent predation mortality rate per drill decreased with increasing density of oysters). Studies on interspecific competition between the two oyster species, as well as other factors, such as presence of alternative prey species, led the authors to conclude that restoration activities for Olympia oysters in Willapa Bay may be limited to areas where drills and naturalized Pacific oysters are absent.

In another study in Willapa Bay, WA, Trimble et al. (2009) studied a remnant population of *O. lurida* to determine what mechanisms might be preventing recovery of the species there.

Their experiments were designed to test four specific hypotheses with regard to growth and survival of oyster spat: (1) recruitment is too low to permit an increase in densities; (2) postrecruitment growth and survival is poor in intertidal habitat; (3) interactions with competitors, particularly non-native species, reduce growth and survival; and (4) stability and density of shell substrate influence postrecruitment performance. Their results suggest that, even though Olympia oysters are sparse in Willapa Bay, recruitment has been relatively high in some areas, but post recruitment survival and growth were poor. They attributed these outcomes to several factors, including aerial exposure, competition from fouling organisms, and absence of subtidal shell accumulations. The authors state that Olympia oyster larvae tend to be attracted to the extensive intertidal beds of *Crassostrea. gigas*, an introduced species, where they are subject to desiccation or freezing and die (i.e., the Pacific oyster beds act as ''recruitment sinks'' for the Olympia oyster), and that the culture of the *C. gigas*, along with the lack of quantities of submerged shell, continues to contribute to the inability of the native oyster to regain its previous abundance.

White, et al. (2009) gathered data on distribution and abundance of *O. lurida* in North Bay Oyster Reserve (on Case Inlet in south Puget Sound, WA), and tested the effects of tidal elevation and substrate on oyster recruitment. They found that a relatively dense population of native oysters with multiple year classes exists in the Reserve and observed successful recruitment on several types of substrates at several tidal elevations. The authors report a clear trend of higher recruitment at lower tidal heights for all substrate types tested, and found that Olympia oyster shell had significantly more spat than bare substrate or gravel, albeit not significantly more than *C. gigas* shell. They suggest that, to obtain the highest recruitment, restoration of *O. lurida* in Washington State is best done at low tidal or subtidal elevations, using shell of *O. lurida* to augment settlement substrate, and it should be done in areas that already contain an adequate density of spawning oysters.

Seale and Zacherl 2009 studied the effects of seawater temperature on settlement of Olympia oyster larvae in two southern California estuaries to test Coe's hypothesis (Coe 1932) that water temperature can be used to predict the initiation and termination of Olympia oyster larvae settlement (i.e., that settlement is initiated at temperatures above 16°C and ceases when water temperatures fall below 16°C). In addition to temperature, the researchers also noted the substrate type, salinity, and tidal elevation at sampling sites. They observed that, even though the temperatures in the two estuaries were very similar, settlement patterns were quite different spatially and temporally, suggesting that temperature is not a predictable cue for settlement and that other factors were involved (e.g., tidal height and salinity). In addition, they noted that estuaries in southern California support reproducing populations of *O. lurida* but have been underutilized heretofore in restoration and monitoring efforts.

Restoration projects can sometimes affect the genetic composition of oyster populations. Camara and Vadopalas (2009) present an overview of relevant genetic concepts, primarily intended to better inform resource managers and restoration practitioners about the potential implications of restoration efforts on population genetics. They describe the various forms and mechanisms of genetic variation, identify a number of human activities that can alter the course of evolutionary change in populations (e.g., by reducing population size, changing patterns of gene flow among populations, and lowering reproductive success), and give examples from finfish and invertebrate aquaculture. They state that, without careful broodstock management, hatchery culture can result in differences in genetic diversity between commercially cultured and wild populations, and caution that the two should remain distinct. The authors also provide a number of practical options for oyster restoration, from a genetic perspective, along with advantages and disadvantages of each, and emphasize the importance of obtaining required data before making a decision about how to proceed. With regard to the Olympia oyster, they note that the species is not in danger of extinction, and is not even an important commercial species right now, so restoration practitioners ''have the luxury of time and of learning from past mistakes,'' and an opportunity to ''get it right'' before implementing restoration strategies.

Much more time, effort, and money have been spent in the past 20 years on restoring the Eastern oyster, *Crassostrea virginica*, than the Olympia oyster, and thus more information on successful restoration techniques is available to those now involved in restoring the Olympia oyster. Lessons learned from *C. virginica* restoration projects, including failed projects, should inform efforts to restore *O. lurida* on the west coast so mistakes are not repeated. In their paper, Brumbaugh and Coen (2009) review some of the causes of declines of the Eastern oyster, *Crassostrea virginica* and discuss the most common restoration techniques used to restore the species in small-scale projects. They stress the importance of having well-defined goals for restoration projects (e.g., provision of ecosystem services or increasing fisheries production), and a robust monitoring program, along with standardized monitoring approaches, to document project outcomes and compare with natural reference sites. The authors cite three major logistical constraints that should be addressed in oyster restoration projects: (1) loose shell is considered to be ''fill'' material in many states, and a permit will probably be required before reef construction begins; (2) fresh shell may contain oyster parasites and should be allowed to age and dry for some time before it is used; and (3) the depth and volume of the shell layer or reef affects the health of the oysters and ultimate success of the project. They also discuss some techniques for addressing recruitment limitations and offer a list of recommendations for those involved in restoration efforts for the Olympia oyster. The authors acknowledge, however, that restoration for *O. lurida* may be more complex because it has a very different life history, there is a lack of historical information about the species, and there are few extant natural populations to study and from which to gather ecological information.

Oyster shell is the material of choice for enhancing and restoring oyster reefs, and untold quantities of *C. virginica* shell have been used in oyster fisheries enhancement and restoration projects for many years along the Gulf of Mexico and Atlantic coasts. The shell has been moved great distances in some cases (e.g., oysters from the Gulf of Mexico are transported to east coast shucking houses and the shell reused there); however, very little is known about the extent to which pathogens, parasites, exotic species, and other organisms inhabit shucked shell and are inadvertently transported to new areas. Cohen and Zabin (2009) provide useful background information on the potential problems accompanying the practice of reusing shell and review the sparse literature available on the subject of survival of marine organisms in shell piles. They also include information on some of the requirements, recommendations, and laws of west coast states regarding the treatment of shell to be transported and reused for restoration and other purposes (e.g., setting hatchery seed). In their own study in San Francisco Bay, California the authors inspected a large pile of *C. gigas* shell (intended for a restoration project) and identified 24 species of dead marine organisms and some live terrestrial arthropods. Although they concluded that the shell was unlikely to harbor exotic species, primarily because of the age of the shell, they note there is no consensus on the length of time that shell should be air dried, and that some marine organisms can survive for months in shell piles (e.g., the oyster parasite, *Perkinsis marinus*, has been observed to survive for months in *C. virginica* oyster tissue adhering to shells). Because of the paucity of studies on this issue, and the increasing demand for oyster shell in restoration activities on all coasts, the authors suggest using a worst-case scenario as the basis for establishing a minimum shell quarantine time. They also recommend more research on this important aspect of oyster restoration, so that adequate protocols can be developed, and transfer of harmful or invasive organisms avoided.

The papers in this volume illustrate some of the progress that has been made in the research and restoration of Olympia oysters on the United States west coast in recent years. They also indicate the need for more studies, and for more educational outreach to increase public awareness of the species as a valuable resource and indicator of the health of west coast estuarine environments. The authors' collective work demonstrates the importance of using the best available science when planning and implementing restoration projects, and confirms that collaboration among the scientific community, oyster industry, and restoration practitioners can be very effective, and is key to the successful restoration of Olympia oysters on the west coast of the United States.

DEDICATION

This special volume is dedicated to two outstanding shellfish biologists: Dr. Kenneth K. Chew, Professor Emeritus, University of Washington, and Dr. Neil F. Bourne, Scientist Emeritus, Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, British Columbia, Canada. In addition to being dedicated scientists, both have also served as role models and mentors to many students and young scientists, worked with various shellfish industries to improve their production, contributed to scientific societies, and given generously of their time in community and public service. The following short biographies are summarized from those published previously in the *Journal of Shellfish Research* (Bourne 2000, Chew 2002).

Dr. Ken Chew received his M.S. and Ph.D. degrees from the University of Washington, after which he joined the faculty of the University of Washington (U.W.) School of Fisheries and served in several capacities from 1962 until his retirement in 2001. His research involved shellfish biology and aquaculture, and he also served as advisor to about 100 graduate students. Ken also cultivated close ties with the Pacific Coast shellfish industry, and much of his and his students' research focused on solving oyster industry problems. He was Director of the Western Regional Aquaculture Center from 1989 to 1996, when he was appointed Associate Dean of the College of Ocean and Fisheries at U.W. His knowledge of shellfish biology and aquaculture extends to many other countries, and Ken is a world-renowned expert in the field; he has consulted with scientists and shellfish growers around the world, helping them improve their aquaculture techniques and production.

An active member in the National Shellfish Association for many years, Dr. Chew served as president in 1971 to 1972, was the first David Wallace Award winner in 1982, and was made an Honored Life Member in 1989, in recognition of his exemplary service to the organization and to the field. Although retired from the University of Washington, Ken is still very busy serving on the Washington Fish and Wildlife Commission, which receives the benefit of his expertise and experience gained over many years as a scientist and as an avid fisherman and hunter.

Dr. Neil Bourne completed his MSc degree at McMaster University in 1953 and, after studying limnology in Germany for a year, returned to Canada to pursue his Ph.D. degree at the University of Toronto. After completing his degree, he joined the staff of the Fisheries Research Board of Canada at the Biological Station in St. Andrews, New Brunswick, where he was in charge of investigating the biology and ecology of sea scallops. He transferred to the Pacific Biological Station in Nanaimo, British Columbia (B.C.) in 1965, where he spent the rest of his distinguished career. Neil studied and published research on the basic biology of Pacific coast molluscs, researched harvesting gear and techniques, conducted surveys of bivalve resources in B.C., and developed aquaculture methods for a number of shellfish species. In addition to his research, Dr. Bourne took time to be actively involved in foreign aid work, serving in Fiji as the Director of a Fisheries Training Program at the University of the South Pacific in Suva, and assisting with several other fisheries projects in other countries, including the Peoples' Republic of China. He also served as affiliate professor and graduate committee member for over 20 students at the University of Washington, University of Victoria, University of British Columbia, and Simon Fraser University.

Neil has received many accolades and awards for his public service and scientific contributions, and has also been a very active member of several organizations, including the National Shellfish Association (NSA). He served as president of NSA from 1981 to 1982, and in 1990 was made an Honored Life Member for his outstanding service to the organization and profession. In 1991 he received the David H. Wallace award from NSA for his work with shellfish industry members. Dr. Bourne retired from the Department of Fisheries and Oceans, Canada in 1994, but remains active in the scientific community and pursuing his favorite hobby, birding.

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