White Paper

Harmful Algal Blooms in the West Coast Region: History, Trends, and Impacts in California, Oregon, and Washington

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This draft report is prepared as guidance material for attendees of the *West Coast Regional Harmful Algal Bloom Summit*. The report will be revised based on edits and comments submitted by attendees and reviewed by the *Summit* Steering Committee. The revision and review protocol will be described at the *Summit.*

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Introduction

Harmful algal blooms (HABs) are a global threat to living resources and human health. The frequency and geographical distribution of HAB events is increasing; they now impact all coastal states. HABs have had significant ecological and socioeconomic impacts on the California, Oregon, and Washington coastal communities for decades, and their prevalence and impacts on living resources in this region have increased markedly over the last 10-15 years (Anderson et al. 2008, Kudela et al. 2008). The types of HABs that continue to threaten West Coast water quality, the health of living resources, and the economies of its communities are widespread and often extend beyond state boundaries (Figs. 1-3). Effective mitigation of the West Coast HAB problem will therefore require a regional holistic approach to coastal ecosystem management, and depend on Federal and state collaboration and coordination.

Recognizing the need for regional collaboration in managing HABs, the West Coast Governors' Agreement (WCGA) on Ocean Health is currently integrating specific actions to promote interstate coordination of HAB research and monitoring efforts in their recently released Action Plan, http://www.westcoastoceans.gov/:

> **Action 1.3**
> *Exchange information between experts in all three states on management tools and techniques to promote development and operation of predictive capabilities of harmful algal blooms and hypoxia. Support the expansion of ocean observing system monitoring efforts amongst the three states for these purposes.*

As part of the strategy, the WCGA Action Plan calls for **a HAB workshop… to reach consensus on the present state-of-knowledge and prioritize the information needed by decision makers to lessen the impacts of the HAB events on humans and critical marine resources.**

The National Oceanic and Atmospheric Administration (NOAA) and the states of California, Oregon, and Washington will convene the *West Coast Regional Harmful Algal Bloom Summit* on 10-12 February 2009 in Portland, Oregon to fulfill the WCGA charge specified in Action 1.3. The *White Paper: Harmful Algal Blooms in the West Coast Region: History, Trends, and Impacts in California, Oregon, and Washington* was developed by the *Summit*'s Steering Committee to summarize the scope of the HAB problem in this region, in order to provide background on the state-of-knowledge for *Summit* Workshop and Public Session attendees. The *Summit* will focus on developing plans for a HAB Monitoring Network and Forecast System encompassing the California, Oregon, and Washington coastal region, but information on HABs in Alaska is included (**History, Trends, and Impacts of PST in Alaska** section) as a geographical extension of similar HAB problems with a long history of living resource and human health impacts.

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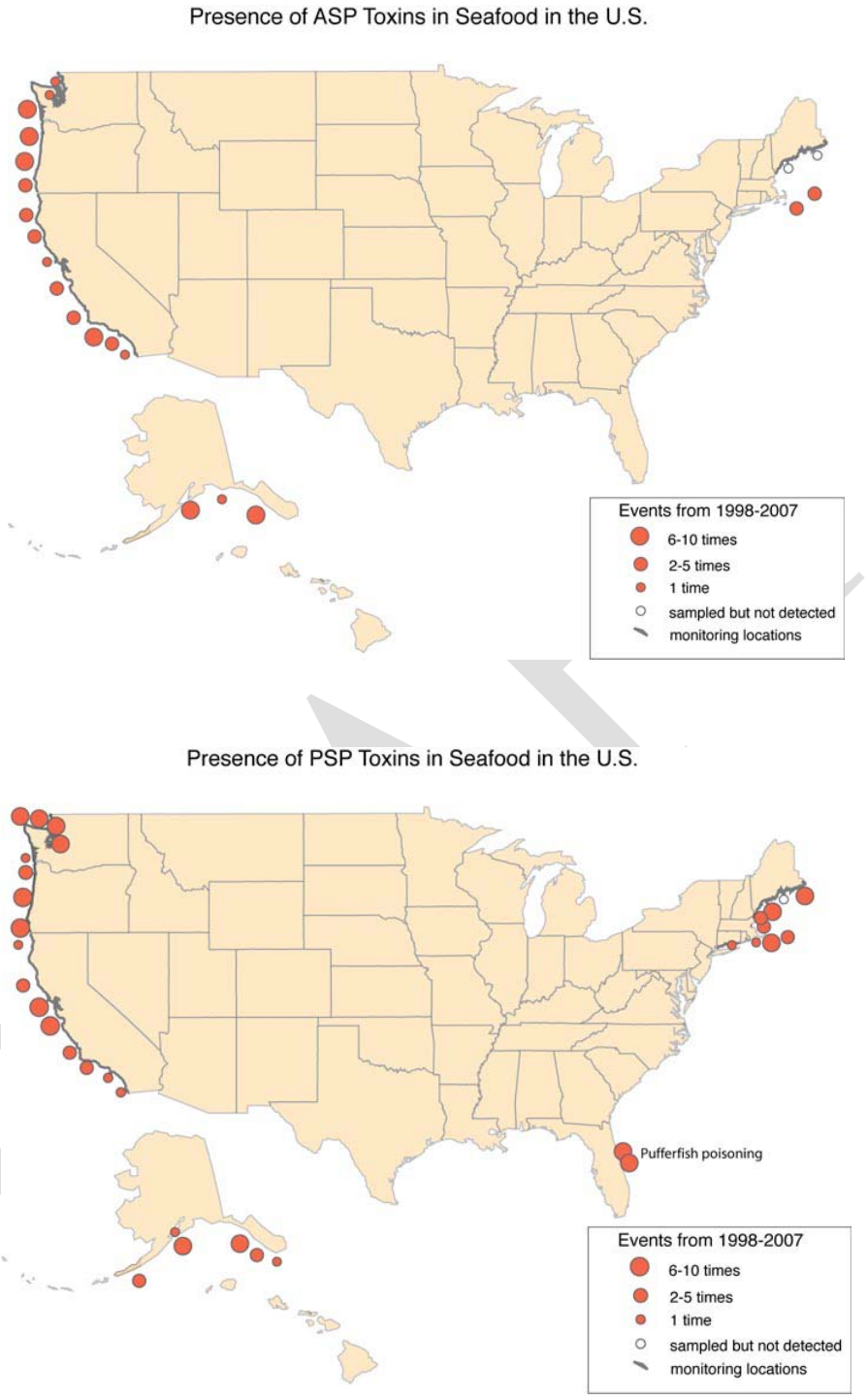
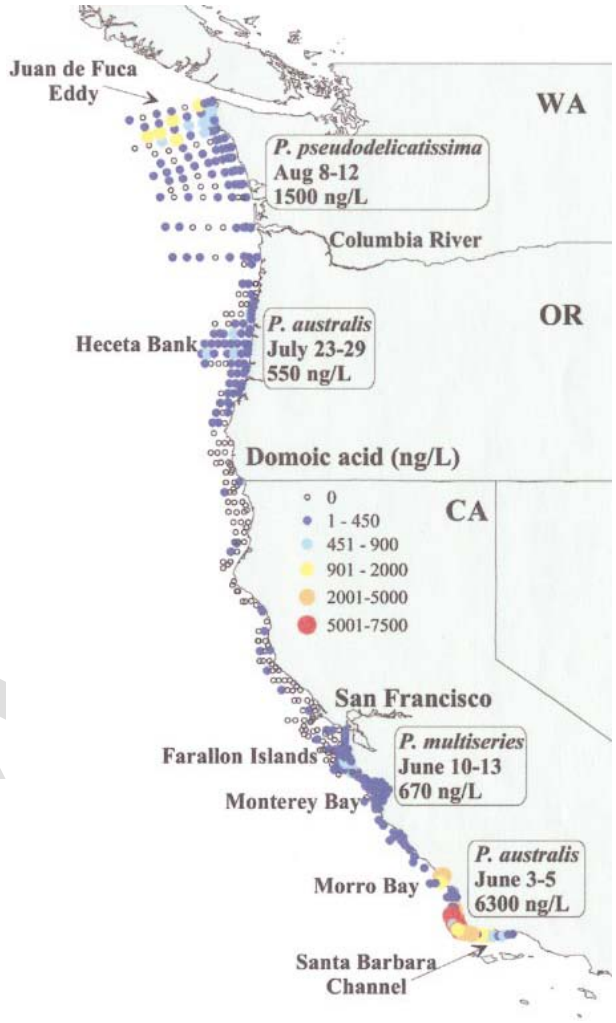


Figure 1. U.S. incidents of seafood toxicity from amnesic shellfish poisoning (top) and paralytic shellfish poisoning (bottom) from 1998-2007. From the U.S. National Office for Harmful Algal Blooms website, http://www.whoi.edu/redtide/

Figure 2. Particulate domoic acid in *Pseudo-nitzschia* species on the U.S. Pacific West Coast in 1998. Maximum concentrations of domoic acid and toxic species are indicated to the right of each area of high toxin. Each of these areas is associated with relatively retentive circulation patterns. From data in figures given in Trainer et al. (2000, 2001, 2002). From Hickey and Banas (2003), their Fig. 7.



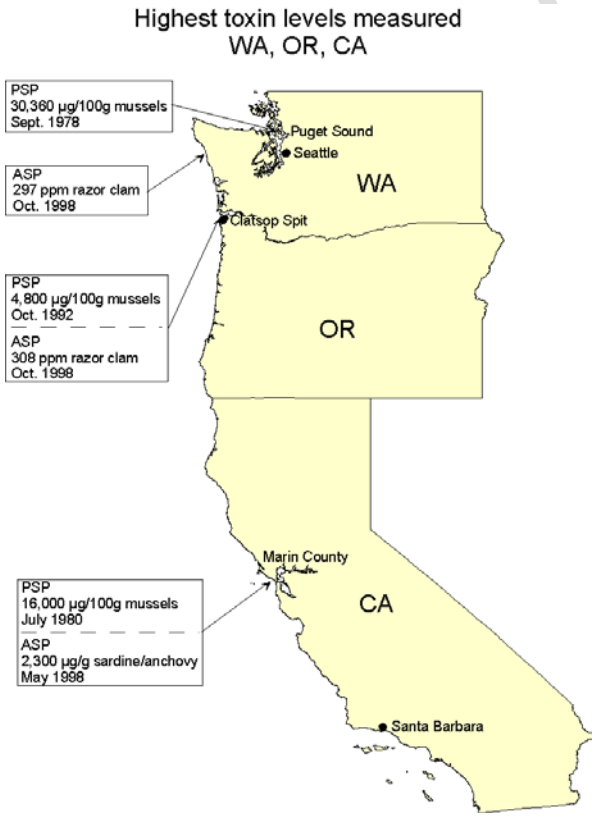


Figure 3. Examples of bloom events where high PST and domoic acid toxin levels were measured. From Trainer (2002), her Fig. 34.

Pseudo-nitzschia **spp. and domoic acid poisoning**

Overview of toxicity, history on West Coast

Several species of the diatom, *Pseudo-nitzschia*, produce domoic acid, a toxin causing amnesic shellfish poisoning (ASP). Of the 12 species of *Pseudo-nitzschia* that have been demonstrated to produce domoic acid, 10 have been reported from West Coast waters (Horner et al. 1997, Anderson et al. 2007). *Pseudo-nitzschia australis* and *P. multiseries* are most commonly associated with toxic events throughout this region, with *P. pseudodelicatissima* and *P. cuspidata* also implicated in toxic events in Washington waters (Adams et al. 2000, Trainer et al. 2009). ASP can result in gastrointestinal and neurological disorders within 24-48 h of toxic shellfish consumption by humans, and can be life-threatening. ASP can lead to short-term memory loss which can be permanent, and other symptoms are similar to (and can lead to misdiagnoses as) other diseases (Washington Department of Fish and Wildlife 2004). For example, disorientation in the elderly has led to misdiagnosis as Alzheimer's disease, and diarrhea, vomiting, and abdominal cramping has been confused with the flu.

Shellfish toxicity due to domoic acid was discovered in 1987, when four people died and 107 became ill from eating contaminated mussels from Prince Edward Island in the Gulf of St. Lawrence, Canada (Bates et al. 1989). However, since then, most of the reported domoic acid events have occurred on the U.S. West Coast. The first documented outbreak on the West Coast occurred in 1991, causing the deaths of dozens of Brown Pelicans and Brandt's cormorants in Monterey Bay and contaminating razor clams and Dungeness crabs in Washington, Oregon, and northern California (Trainer et al. 2002). In southwest Washington alone, crab fishing losses were estimated at $7 million. Although no one died from the 1991 outbreak, it is thought that 25 human illnesses in Washington were attributable to ASP (Washington Department of Fish and Wildlife 2004).

After these early ASP events, monitoring efforts and regulation to prevent harvesting toxin contaminated shellfish have succeeded in limiting human incidents of ASP, but numerous cases of domoic acid toxicity of finfish, marine mammals, and birds have been documented on the West Coast. Several shellfish and finfish have been reported as potential vectors of the disease, including razor clams, Dungeness crabs, blue mussels, littleneck clams, geoduck clams, manila clams, Pacific oyster, anchovies, and sardines. In addition to commercially harvested species, many other animals have been found to accumulate domoic acid, leading to widespread transfer through marine food webs (e.g. Lefebvre et al. 2002, Bargu and Silver 2003, Bargu et al. 2008, Kviteck et al. 2008). Death or illnesses have been reported in California sea lions, northern fur seals, harbor porpoises, common dolphins, sea otters, gray whales, Brown Pelicans, Brandt's cormorants, black-crowned night herons, Pacific loons, red-throated loons, common loons, rhinoceros auklets, Cassin's auklets, ruddy ducks, surf scoters, short-tailed shearwaters, western grebes, and Clark's grebes (F.M.D. Gulland, unpub. data for marine mammals – e.g. Fig. 4; D.A. Caron, unpub. data for birds).

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Trends in prevalence and impacts

Pseudo-nitzschia have been documented on the West Coast since phytoplankton collection began in 1920 (Fryxell et al. 1997). Over the last 15 years, numerous blooms of *Pseudo-nitzschia* on the West Coast have been reported, and associations with domoic acid and animal deaths and illnesses frequently documented (Scholin et al. 2000, Gulland et al. 2002, Trainer and Hickey 2003, Goldstein et al. 2008). Besides the first coast-wide event in 1991, another exceptional and widespread event occurred in 1998 (Fig. 2), when marine mammal deaths attributed to domoic acid were first documented (e.g. 81 California sea lions from San Luis Obispo to Santa Cruz), and high levels of domoic acid were measured in Washington and Oregon razor clams (Adams et al. 2000, Scholin et al. 2000). In California, domoic acid outbreaks have occurred in almost every year over the last decade (e.g. Fig. 4).

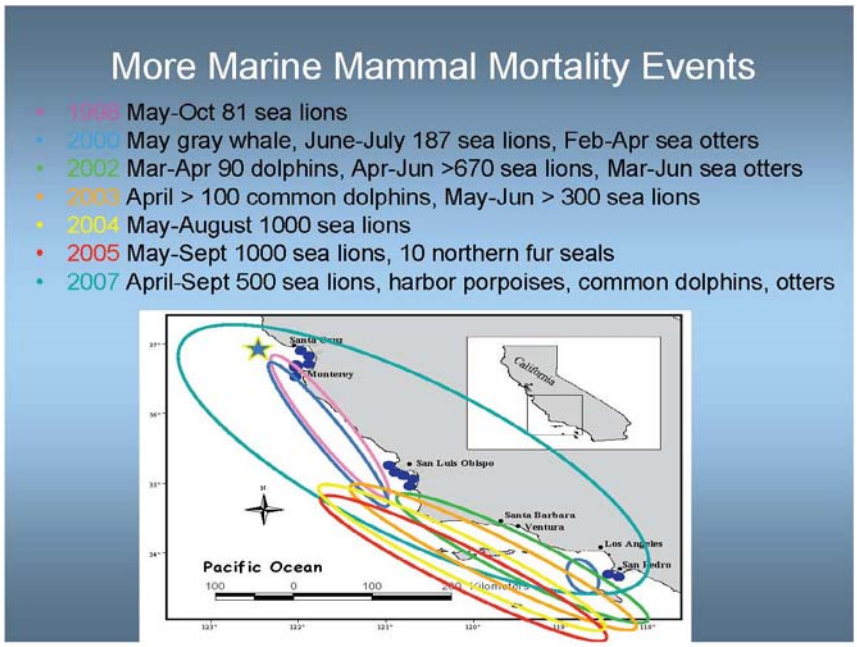

Figure 4. Marine mammal mortalities attributed to domoic acid toxicity from 1998 to 2007. With permission from F.M.D. Gulland, unpub. data.

Washington

Toxic *Pseudo-nitzschia* blooms have caused severe economic losses on coastal Washington (including tribal) communities from beach and shellfish harvest closures. Impacted areas span the coast, with a demonstrated "hot spot" in the Juan de Fuca eddy area, where *Pseudo-nitzschia* blooms occur relatively frequently, associated with high domoic acid concentrations (Trainer et al. 2002). This area is a chronic upstream source of toxic *Pseudo-nitzschia* for the Washington coast (Trainer et al. 2002, 2007, 2009, Marchetti et al. 2004).

Exceptional years of domoic acid-associated beach, razor clam, and Dungeness crab closures in Washington include: a) 1991, when closure of beaches to recreational and commercial razor clam and Dungeness crab harvesting resulted in a $15-20 million revenue loss to fisheries; b) 1998-1999 (over a year and a half), when fishery closures caused Washington's Quinault tribe to lose all of their razor clam income and a large portion of their Dungeness crab income, and the Quileute tribe to lose 50% of their Dungeness crab income; c) 2002-2003, another prolonged closure period (> 1.5 years) that

resulted in a $10.4 million loss in revenue; and d) 2005, when toxic blooms of *P. pseudodelicatissima* and *P. australis* caused significant commercial, recreational, and tribal shellfish harvest losses in Sequim Bay and Penn Cove areas of Puget Sound, respectively (Horner and Postel 1993, Anderson 1995, Wekell and Trainer 2000, Trainer et al. 2009). In fact, the highly abundant toxic *Pseudo-nitzschia* blooms have only recently (2003 and afterward) been reported in Puget Sound, causing great concern that continued escalation/expansion will impact the many valuable fisheries there (Trainer et al. 2009). The total estimated impacts of a coastwide seasonal closure of the recreational razor clam fishery for 2008 was $21.9 million and the income impact of the recreational razor clam fishery in Washington State for 2008 was $13.5 million (Huppert and Dyson 2009).

Oregon

In addition to Washington's Juan de Fuca area, other chronic sources of toxigenic *Pseudo-nitzschia* (i.e. "hot spots") include the Heceta Bank and the Columbia River outflow (Clatsop) areas of Oregon (Strutton, unpub. data; e.g. Fig. 2). Like Washington, the 1998 and 2003 events caused beach closures of razor clam and Dungeness crab harvesting that lasted > 1.5 years, and in 2003-2004, led to a $4.8 million loss to the Oregon razor clam industry at Clatsop Beach alone (Oregon Department of Fish and Wildlife; http://www.dfw.state.or.us/MRP/shellfish/razorclams/Biotoxins.asp). The impact of domoic acid toxicity on razor clam, mussels, and Dungeness crab industries appears to be increasing in recent years, with exceptionally extensive and prolonged closures occurring from 2003-2005.

California

After the 1998 event when domoic acid was first linked to sea lion deaths, toxic blooms and associated mammal and bird illnesses on the California coast have occurred in nearly every year since (e.g. Fig. 4). For example, toxic *Pseudo-nitzschia* blooms have been recorded in the Santa Barbara Channel in every year since 2002, and off Los Angeles in every year since 2003 (Anderson et al. 2007, Schnetzer et al. 2007). Blooms of *P. australis* off southern California in 2006 and 2007 were characterized by some of the highest planktonic domoic acid concentrations ever measured (Caron 2008). Since 2003, hundreds of marine mammal and bird strandings or deaths from central to southern California have been attributed to domoic acid, and there is evidence that these poisonings are increasing. For example, Caron (2008) reported domoic acid toxicity in several bird species for the first time in 2006-2007. Spring 2007 was cited as the worst season for marine mammal and bird mortality on the southern California coast (International Bird Rescue Research Center, http://www.ibrrc.org/pr_04_25_2007.html).

Domoic acid has been detected in seafood species (bivalve shellfish, sardines, anchovies) almost every year since the 1991 episode (Langlois 2007). Concentrations of domoic acid exceeding the federal public health alert level (20 ppm) have been detected in seafood species every year between 2000 and 2007, primarily between San Luis Obispo and Los Angeles counties. In 2007, domoic acid concentration of 610 ppm was detected in mussels from Santa Barbara, the highest level ever recorded in California (Langlois 2007).

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The most persistent problems with elevated domoic acid concentrations have been in the Santa Barbara-Ventura region, extending offshore to the Channel Islands.

Based on examination of 715 sea lions with neurological symptoms collected between 1998 and 2006, Gulland (2008) identified two domoic acid syndromes, an acute domoic acid toxicosis and a chronic epileptic syndrome. Clusters of strandings of acute syndrome cases were found in 1998 (centered in Monterey Bay), and 2000, 2001, 2002, and 2005 (centered off San Luis Obispo and Santa Barbara counties). While an increasing trend in acute cases from 1998 to 2006 was not found, chronic cases were found to increase in every year, from 4 cases in 1999 to 45 cases in 2006. These data indicate that the impacts of domoic acid on sea lions have continually increased in recent years.

***Alexandrium catenella* and paralytic shellfish poisoning**

Overview of toxicity, history on West Coast

Paralytic shellfish poisoning (PSP) is caused by a suite of biotoxins, collectively called the paralytic shellfish toxins (PSTs), produced by species of the dinoflagellate genera, *Alexandrium, Gonyalaux,* and *Pyrodinium.* On the U.S. West Coast, *Alexandrium catenella* is the species typically associated with toxic outbreaks. PSP symptoms are neurological, and onset is rapid and can result in paralysis or death (e.g. through respiratory arrest). Toxicity varies with shellfish species, and some of the species most likely to be contaminated include mussels, butter clams, geoduck clams, Pacific oysters, and razor clams, but several other species have been reportedly contaminated, including but not limited to littleneck clams, purpled hinge rock scallop, Dungeness crabs, whelks, gooseneck barnacles, horse clams, moon snails, and spiny lobsters (Deeds et al. 2008). PST have also been detected in the clupeoid fish, northern anchovies and Pacific sardines.

Human deaths due to PSP poisoning date back to 1791-1792, when several crew members of Captain George Vancouver's Royal Navy died after eating shellfish from a beach near modern day Vancouver, British Columbia. Human poisonings from PSP were first reported in coastal California in 1903, when 12 people became ill after eating mussels in Sonoma County, and 5 of these died (Sommer and Meyer, 1937). In 1927, a major outbreak occurred along a multi-County region north and south of San Francisco (102 illnesses, including 6 deaths). From 1927 through 1989, the PSP related illnesses have totaled 510 in California, including 32 deaths (Price et al. 1991). In Washington, the earliest reported PSP poisonings were of Native American children dying from shellfish consumption in the Strait of Juan de Fuca in 1942 (Trainer et al. 2003). In Coos Bay, Oregon, PSP poisonings caused 20 illnesses and 1 death in 1933 (Nishitani and Chew 1984).

Trends in prevalence and impacts

Alexandrium catenella outbreaks, and associated shellfish toxicity and human illnesses have been a persistent problem throughout the West Coast for decades, and the frequency and geographic distribution of associated shellfish closures has increased since

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monitoring first began in the 1940s and 1950s (Trainer et al. 2003); Fig. 5. Over the last 20 years, however, evidence does not support an increasing trend in bloom prevalence or magnitude; e.g. in Puget Sound (Moore et al. 2009) or central California (Langlois 2007). In contrast, the magnitude and impacts of ASP outbreaks due to *Pseudo-nitzschia* blooms increased during this same time.

Washington

In Washington, PST-related closures of shellfish harvesting have been imposed since the 1942 incident that led to Native American fatalities in the Strait of Juan de Fuca. In the 1950's and 1960's, toxic blooms of *Alexandrium* were widespread and prevalent in the northern regions of Puget Sound (e.g. Sequim and Discovery Bays), but extended southward in the 1970's and 1980's to the inner Sound (Trainer and Hickey 2003, Cox et al. 2008, Trainer et al. 2009). Commercial shellfisheries in Puget Sound have been closed

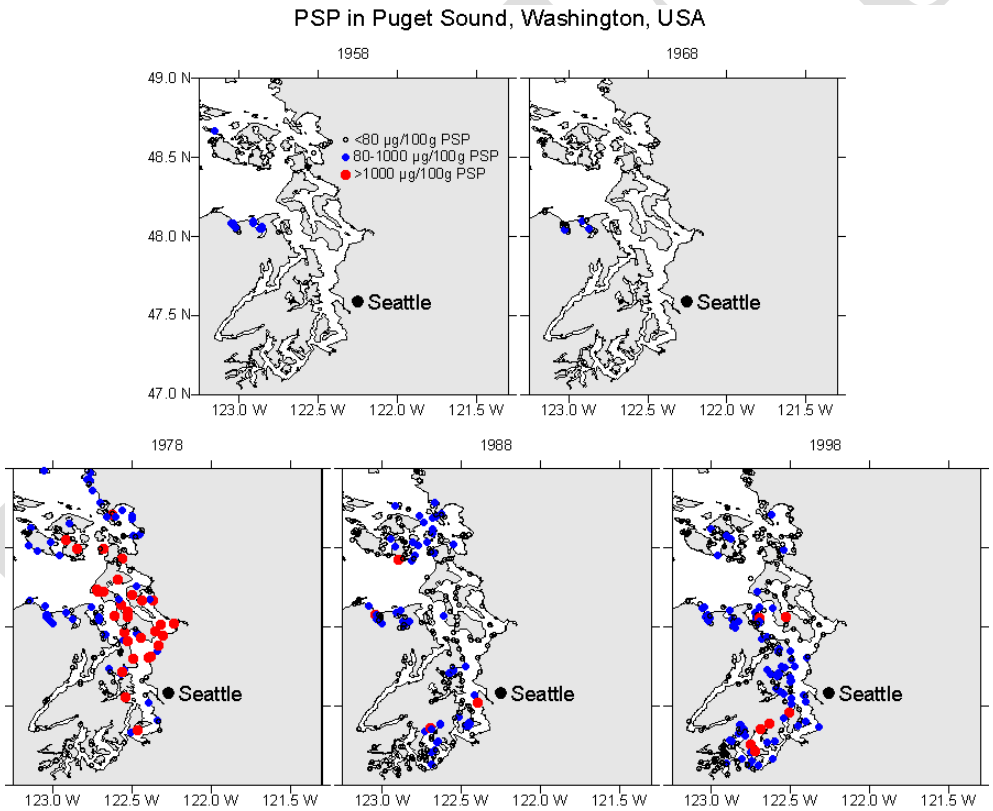

Figure 5. PST closures in Puget Sound over the past 5 decades. Black circles are open sites (below the regulatory closure level of 80 µg saxitoxin equivalents per 100 g shellfish), and blue and red circles are closed sites (greater than or equal to 80 µg/100g). From Trainer et al. (2003).

frequently at several sites since PSP monitoring began there in the late 1950's. On the outer coast of Washington, commercial shellfishery closures are less frequent (approximately once every 5 years), but recreational shellfish harvesting on the outer coastal beaches is closed annually from 1 April until 31 October as a preventive measure.

Ceremonial, subsistence, and commercial harvests by Washington's tribal communities have been greatly impacted by PST-associated shellfish closures (Wekell and Trainer 2002). The Puyallup, Suquamish, and Jamestown S'Klallam Tribes have experienced severe economic losses from their commercial geoduck fisheries, based on frequent and lengthy seasonal harvest closures. Commercial harvesting of oysters and Dungeness crabs by the Jamestown S'Klallam Tribe, and of clam, oyster, and cockles by the Lummi Nation have also been significantly affected. Subsistence and ceremonial harvesting by the Jamestown S'Klallam Tribe have been impacted by PST toxicity of butter, littleneck, horse and manila clams. Beach closures have also impacted Puyallup Tribal culture by restricting the use of clams for ceremonial dinners at weddings and funerals.

Oregon

In Oregon, monitoring of shellfish for saxitoxins has been routinely conducted since 1979, leading to frequent closures, primarily of razor clam and mussel shellfisheries. As with domoic acid, PST has severely impacted shellfish harvests at Clatsop Beach in northern Oregon (Tweddle et al. 2008; P. Strutton Laboratory website; http://bioloc.oce.orst.edu/strutton/orohh_anim.htm). For example, a PST outbreak in this region caused the closure of razor clam harvesting from 2002-2004. In any given year, the type of HAB outbreak may vary between northern and southern Oregon coastal areas. In 1992, a PST event affected the central and northern coast, but not the southern reaches, and in 2001, PST affected the southern beaches, while domoic acid impacted the northern beaches only.

The frequency and duration of PST-related shellfish closures on the Oregon coast have increased over the period from 1979 to 1996 (Strutton et al. 2007; Oregon Department of Fish and Wildlife; http://www.dfw.state.or.us/MRP/shellfish/razorclams/Biotoxins.asp; P. Strutton Laboratory website; http://bioloc.oce.orst.edu/strutton/orohh_anim.htm). Twice as many closures occurred from 1990-1996 as prior to then, and most of these lasted more than 50 days.

California

PST toxicity has been documented in coastal California since the 1920's, with the geographic center in central California (Marin County at Drakes Bay), although PST in shellfish is frequently reported in the other coastal counties (Price et al. 1991, Langlois 2006). It is noteworthy that domoic acid has only rarely been detected in Marin County shellfish. The greatest period of PST activity extended through the 1980's into 1991; since that time there has continued to be persistent, but smaller magnitude events typically

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limited to a smaller geographic range (e.g. Fig. 6). There has been a geographic shift however, with increased frequency and concentration of the PST south of Pt. Conception where these toxins have not previously been a significant problem (Langlois 2006), and a temporal shift, with an increase in late winter peak toxicity in these southern waters.

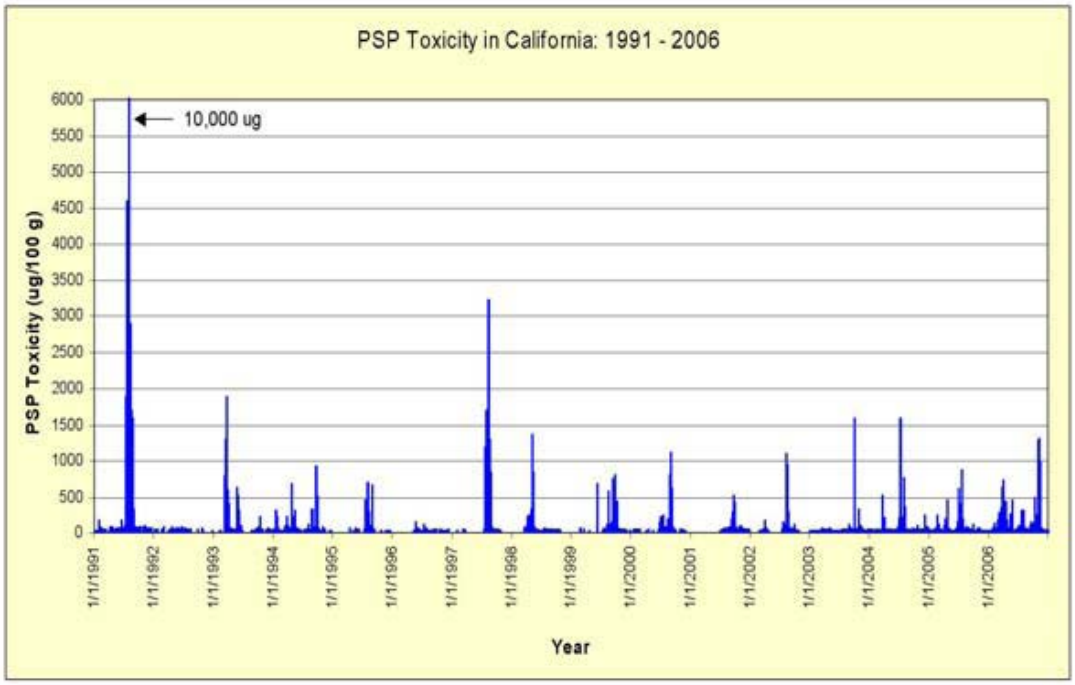

Figure 6. PST toxicity in shellfish collected from California coastal waters between 1991-2006 (from Langlois 2006; http://www.cdph.ca.gov/HealthInfo/environhealth/water/Pages/Shellfishreports).

Heterosigma akashiwo and fish kills

Blooms from the raphidophyte, *Heterosigma akashiwo* have been associated with massive finfish kills in temperate waters worldwide. In the northeast Pacific (Washington and British Columbia), commercial fishery losses have been substantial since the 1960's, primarily to aquaculture. The mechanism for *H. akashiwo* toxicity is not well established however several modes of toxicity have been proposed and researched in laboratory settings, including production of brevetoxin-like compounds (Khan et al. 1997, Keppler et al. 2006), mucus or lectin-like polysaccharides (Pratt 1966, Chang et al. 1990), reactive oxygen species such as superoxide and hydrogen peroxide (Yang et al. 1995, Twiner and Trick 2000) and hemaglutinating and hemolysing compounds (Onoue and Nozouwa, 1989).

In Washington State, Puget Sound aquaculture fisheries have been severely impacted by *Heterosigma* over the years (Horner et al. 1997, Rensel 2007). The first fish

kill associated with a *Heterosigma* bloom in Puget Sound occurred at Lummi Island in 1976. A major salmon kill occurred in the Sechelt Inlet (British Columbia) region of Puget Sound in 1986, resulting in a loss of approximately 1/3 the population and $2.5 million in lost revenue. In 1989, another massive bloom led to a $4 million loss in caged fish in British Columbia and another $4 million off Cypress Island, Washington. Aquaculture fish losses were also severe in central Puget Sound in 1990, when 1.3 million fish and $5 million revenue were lost (85-100% population losses per pen), that included an endangered species, white river spring chinook brood stock. Widespread blooms also occurred in 2006 ($2 million loss in farmed fish) and 2007. From 1994 on, *Heterosigma* bloom associated mortalities in wild salmon and other fish were also documented (Hershberger et al. 1977, Horner et al. 1997, Rensel 2007).

Although *H. akashiwo* blooms have been reported on the California coast, impacts to fisheries have only been documented in Washington and northward; however, this may be related to the relative lack of aquaculture facilities in affected California regions (e.g. San Francisco Bay, Monterey Bay, and Southern California).

Other HABs

Several other HAB species are widespread along the West Coast but historically bloom formation, toxin production, and ecosystem or human health impacts by these species have been rarely reported. However, recent observations suggest possible future impacts, and West Coast regional monitoring programs should include emphasis on their detection. Such HAB species include the dinoflagellates, ***Dinophysis* (diarrhetic shellfish poisoning)**, ***Cochlodinium* (fish kills, toxic mechanism unclear),** and ***Protoceratium reticulatum, Lingulodinium polyedra,* and *Gonyaulax spinifera* (yessotoxin producers).** Also, in the upper reaches of some estuaries, the cyanobacterium, ***Microcystis aerugillosa***, has emerged as a major bloom-former recently.

Several species of *Dinophysis* are commonly found in West Coast waters that have been documented to produce okadaic acid and cause diarrhetic shellfish poisoning (DSP) in other parts of the world (e.g. *D. acuminate, D. acuta, D. fortii, D. norvegica*). Symptoms of DSP include mild to severe gastrointestinal illnesses and although no deaths have been documented, DSP is known to be a strong tumor promoter. Although toxic effects from these species has not been demonstrated on the West Coast, testing for okadaic acid is not routine and toxic effects can be mild and misdiagnosed. Recently, okadaic acid was detected in mussels off Santa Cruz Wharf (Miller et al. 2008).

Two species of *Cochlodinium* have widespread distribution on the West Coast but only recently were linked to fish kills there. *C. polykrikoides*, which has been a major cause of fish kills off Japan, China, and Korea, was linked to a kill of aquacultured Atlantic salmon in British Columbia in 1999-2000 (Whyte et al. 2001). More recently, a bloom of *C. catenatum*, was linked to a 2004-2005 mussel mortality event in Monterey Bay (Curtiss et al. 2008). This species is known for causing fish kills on the Pacific coast of Mexico and Central America.

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Yessotoxin (YTX) is a new class of lipophilic biotoxins shown to be a tumor promoter in mice but with unknown effects on humans. It is produced by three cosmopolitan bloom-forming dinoflagellates, *Protoceratium reticulatum*, *Lingulodinium polyedra*, and *Gonyaulax spinifera*. Recently, YTX was detected in West Coast waters, in non-bloom conditions near Grays Harbor, Washington in 2004 (Howard et al. 2008), in isolates of *L. polyedrum* and *G. spinifera* from coastal California (Armstrong and Kudela 2006, Howard et al. 2008), and in mussels from Scripps Pier during a bloom of *L. polyedrum* and from Monterey Bay in 2005 (Howard et al. 2008). *P. reticulatum*, which is known to have significant impacts on the shellfish industry in British Columbia, was documented in bloom abundance in north Puget Sound in 2006.

Starting in the late 1990s, massive *Microcystis aerugillosa* blooms have recurred in the upper San Francisco Estuary (Lehman and Waller 2003) and Klamath River Estuary, Oregon. These are not restricted to very low salinities, and can be abundant in water with salinity as high as 18. Blooms were associated with microcystin detection in the water, zooplankton, and clam tissue, and production from isolates. A massive bloom occurred along the entire length of the Klamath River in 2005 (Fetcho 2006, 2007). The cyanobacterium is a major concern for the Yurok Tribe because the timing of the bloom coincides with the adult Chinook Salmon run, which has subsistence and commercial value for this tribal fishery.

Macroalgal blooms have been documented in a number of Pacific coast estuaries, but data are lacking for many areas (Bricker et al. 2007). These blooms develop high biomass in shallow water and sea grass habitats, shading other vegetation and negatively impacting animals through hypoxia formation or, possibly production of toxic secondary metabolites. Examples of macroalgal blooms from invasive species have been documented recently in the San Juan Archipelago of Washington (*Sargassum muticum*) and lagoons in southern California (*Caulerpa taxifolia*) that have displaced native algal species and modified habitat, leading to losses in living resources and economic costs for eradication (Jousson 2000, Britton-Simmons 2004, Klinger et al. 2006, Walters et al. 2006). Although these are a significant and growing problem, the research and response requires different strategies than microalgal HABs, so Action Plans to address macroalgal HABs will be developed at a separate, cross-regional workshop in the near future.

History, Trends, and Impacts of PST in Alaska (from Trainer 2002 and R. RaLonde personal communication)

<u>Domoic acid</u>

Alaska does not have a formal environmental monitoring program to identify or forecast occurrence of *Pseudo-nitzschia* blooms, nor a sampling and testing program to measure domoic acid levels in personally harvested shellfish. The Alaska Department of Environmental Conservation (ADEC) is the only agency responsible for marine biotoxin testing in shellfish, with sampling restricted to commercially harvested and aquaculture products. ADEC tests between 600-700 samples annually; however, testing is primarily conducted on Pacific oysters and geoduck clams, poor candidates for monitoring domoic acid. Phytoplankton monitoring in Alaska has historically concentrated on the spring

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bloom period, primarily to understand the influence of ocean productivity on marine fish survival. Since *Pseudo-nitzschia* is not a major component of the spring bloom, data on the locations, timing, and intensity of *Pseudo-nitzschia* blooms is rare.

Domoic acid is present in Alaska, and anecdotal evidence seems to indicate its potential for expansion. The only positive test for domoic acid occurred in a razor clam sample taken in Kachemak Bay near the community of Homer, Alaska in 1997 measuring 11.5µg/g. A single 2006 incident of a person consuming shellfish harvested from Kachemak resulted in hospitalization with neurological symptoms 48 hours later and additional examination confirmed hippocampus damage. Positive domoic acid testing results from ill or dead marine mammals are becoming more frequent. The impact of domoic acid on human and marine ecosystem health is unknown, and not knowing the potential risks to human health and the environment is disturbing.

As a starting point to investigate the occurrence of domoic acid in shellfish, a recently funded North Pacific Research Board (NPRB) project will conduct a coast-wide testing project during the summer and fall of 2009. Intensive sampling will occur at location of high risk and volunteer samples supplied by partnerships will be test at no cost.

PST

Paralytic shellfish poisoning is a pervasive problem in Alaska, particularly for coastal Native shellfish harvesters. Three species of PST producing *Alexandrium* occur in Alaska. *A. catenella* occurs from southern California to southeast Alaska, forms chains, blooms when the water temperature is about 20°C, and occurs in both estuarine and open coast environments. *A. tamarense* prefers cooler temperatures and less saline waters than *A. catenella*, and has been found in the Gulf of Alaska (RaLonde 1996). *A. fundyense* has been found at Porpoise Island, Alaska.

From 1973 to 2008, 204 cases of PSP illness were reported (Fig. 7) but under reporting of illness is likely. Gessner and Schloss (1996) estimated that actual illnesses may be as much as 10-30 times the number of reported cases. In outbreaks where species were known, most involved the ingestion of butter clams and mussels. Cockles, razor clams, and littleneck clams were also eaten and caused some of the illnesses. Most outbreaks of PSP occurred on Kodiak Island, the southern edge of the eastern half of the Aleutian Islands and Southeastern Alaska. No outbreaks of PSP have yet resulted from shellfish collected from Cook Inlet.

Shellfish south of the Aleutian chain often have high toxin levels whereas areas north of the chain are often toxin free. Generally, areas have lower levels of PST in the spring and fall (Fig. 8, example from 2000), while summer and early winter are times when high levels of PST are generally observed. However, some exceptions exist. In Steamboat Bay (SE Alaska) and Grabina Island (outside Ketchikan), geoducks are toxic all year. In Simons Bay (outside Sitka), there was one peak level of PST in Jan 1996 (240 µg/100g), but this area is generally free of PST. The highest level of PST ever measured in Alaska was 20,606 µg in blue mussels at Kamisan Bay, Kodiak Island on May 27, 1997 (Fig. 9).

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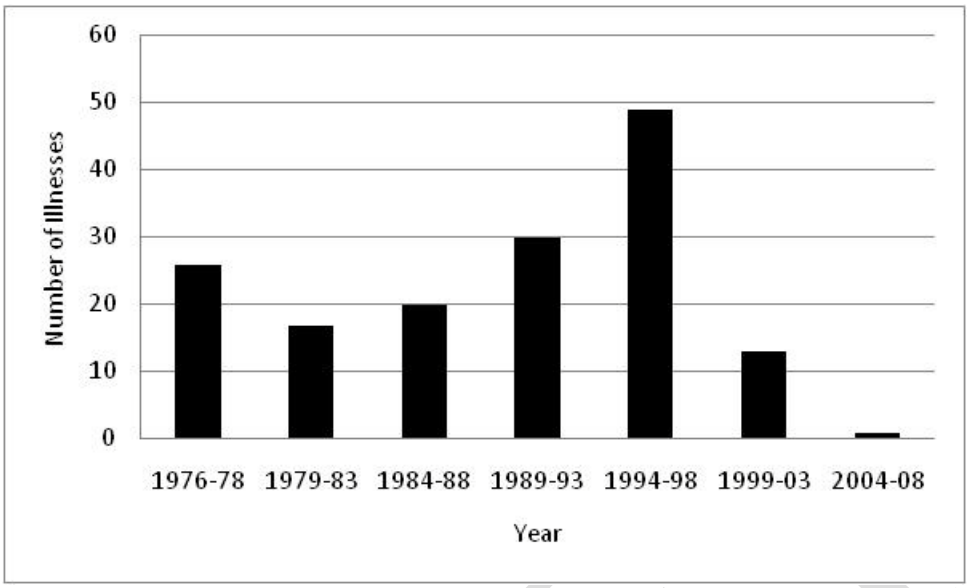


Figure 7. Alaska PSP illnesses reported to ADE since 1976.

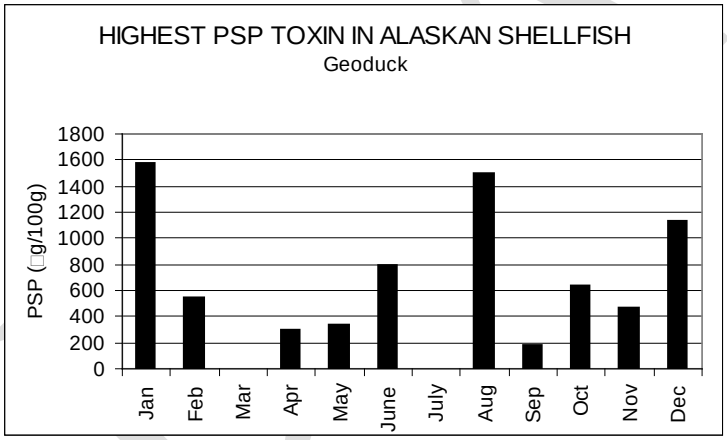
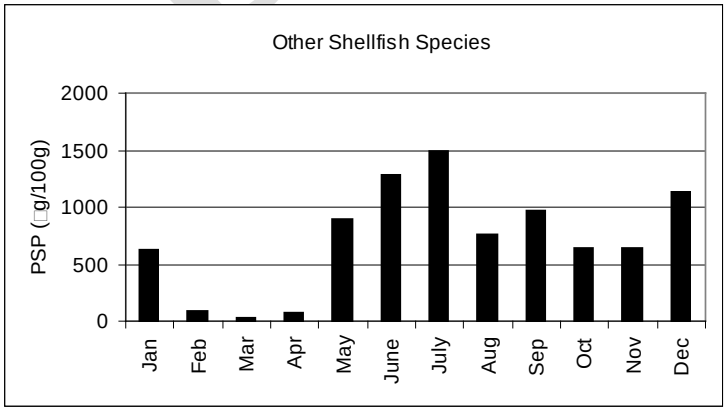


Figure 8. Highest PSP toxin in Alaska by month for the year 2000.



Some relatively high PSP levels in shellfish species tested are shown in Figs. 9 and 10. There has been some recent documentation of PST in Alaska where no prior occurrences have been seen. Levels of PST in oysters have recently been measured in areas of SE Alaska where previously there was no problem.

Alaska has the largest, most productive fishery (shellfish and fish) in the U.S., contributing 54% to the total U.S. landings. The cost of PST to the commercial fishery, recreational harvest, and aquaculture surpasses $10 million annually (RaLonde 1996). The economic consequences of PST in Alaska have drastically impacted the development of a clam fishery where an estimated 50 million pounds are available for harvest (U.S. Department of Interior 1968). In 1917, five million pounds of shellfish were harvested from Alaskan waters, but today the state's commercial bivalve industry is virtually nonexistent. The impact of PST on Alaska's current shellfish fishery is exemplified by the reduced value of the geoduck fishery. In 2002, the ex-vessel value of geoduck was $0.72/lb when live sale of clams composed only 10% of the harvest. The remainder of the harvest was processed after eviscerating and freezing the clams due to high PST levels contained in the visceral mass. In 2004, regulatory modification enabled live sale of 50% of the harvest, increasing the ex-vessel value to $4.09/lb.

The potential problem of PST and testing requirements are major factors preventing development of a surf clam harvest in the Bering Sea. The sustainable harvest of the Bering Sea surf clam is estimated at about 29,000 metric tons with an annual worth of about $9 million (Hughes et al. 1977). The harvest of other clam species that are affected by PST and net worth of these fisheries is shown in Table 1. Income is based on ex-vessel price paid to the fishermen and is averaged over the fishing season price (Frenette et al. 1977).

Because of the alarming impact of PSP on human health, in 1995 the Alaska Sea Grant Marine Advisory Program (MAP) launched an aggressive outreach program to reduce the risk of PSP encounters by shellfish harvesters. MAP has concentrated on public education, assisting with development of the Jellet Rapid Test Kit for field testing, and conducted research to expand the know range and concentration of PSP toxin. Since 1995, MAP has conducted 26 statewide workshops, distributed over 5,000 copies of the publication "Paralytic shellfish poison toxin: The Alaska problem", sponsored two national conferences with published proceedings, conducted field testing, and assisted in planning four short-term monitoring programs. The impact of the MAP program may have been a contributing factor in the reduction of PSP illnesses (Figure 1)

In 2008-9, a North Pacific Research Board (NPRB) funded a bivalve sampling program along the entire coast of the North Pacific and the Pribilof Islands. Of the 106 samples tested, 10.4% were above the 80 µg/100g regulatory limit. Assessment of traditional knowledge as a preventative measure revealed that methods employed by local harvesters actually put them at greater risk of encountering PSP (Wright and RaLonde in press). The NPRB study exposed a serious potential for expansion of PSP illness that can result from Alaska Native sharing of subsistence harvest. The most significant example was evident in the small Aleutian Peninsula community of King Cove, Alaska. With a population of only 800 citizens, a community supported program regularly harvests clams and distributes them to a number of communities in Alaska and along the west coast. King

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Cove has documented cases of PSP illness; one case involved a fatality in 1990 when the harvester consuming butter clams with a PSP concentration of 2,650 µg/100g. Subsequent, sampling from the suspected beach found PSP toxin levels as high as 7,750 µg/100g (CDC 1991). The NPRB study measured levels approaching 65 µg/100g (Wright and RaLonde in press). This small case study shows that a small community, legally harvesting and distributing thousands of clams, can have an enormous human health impact across a large geographical area. Realizing the potential impact, King Cove has initiated a PSP monitoring and testing program.

Figure 9. Locations and levels of relatively high PST toxin measured in blue mussel, butter clam, Dungeness crab, cockle, and littleneck clam.

Figure 10. Locations and levels of relatively high PSP toxin measured in razor clam, geoduck, softshell clam, oyster, surf clam, horse clam, and scallop.

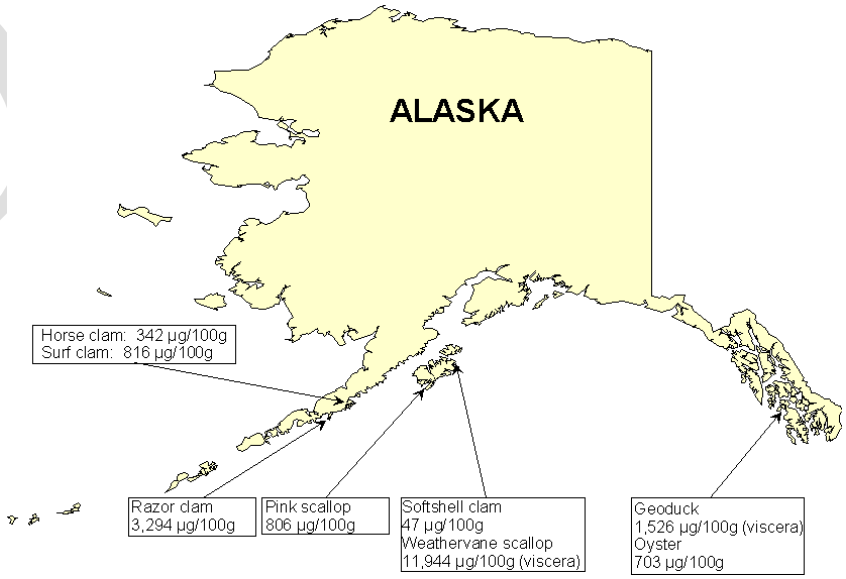

Table 1. Average commercial clam harvest in pounds (thousands) and income in US dollars (thousands), 1990-1999.

Littleneck clam				**Razor clam**		**Geoduck clam**	
Southeast Alaska		*Kachemak Bay*		*Cook Inlet*		*Southeast Alaska*	
Harvest	Income	Harvest	Income	Harvest	Income	Harvest	Income
7.6	21.3	50.7	68.4	289	156.1	222	499.5

Benefits of a Regional HAB Monitoring Network and Forecast System to Management

Several monitoring and forecast systems exist on the West Coast that provide information for decisions by public health and resource managers. Although progress has been made in intrastate coordination (e.g. Olympic Regional HAB Partnership, ORHAB, and the recently formed California HAB Monitoring and Alert Program, HABMAP), and interstate coordination (e.g. Northwest Association of Networked Ocean Observing Systems, NANOOS), tri-state coordination in HAB monitoring, alert, and forecasting is lacking. A regionally integrative and comprehensive approach is needed to improve management capabilities to rapidly and efficiently detect, disseminate information, and respond to HABs, and to provide more accurate and timely predictions of potential impacts.

Benefits of a Regional Monitoring Network and Forecast System to resource and public health managers include:

- the timeliness of HAB warnings will be improved by interstate dissemination of data on HAB species and toxin occurrence and concentration;

- the efficiency of HAB monitoring would be improved, and the cost decreased, by a regional network because redundancy in sampling would be reduced and targeted sampling would be enhanced by transfer of information on bloom transport;

- development and validation of forecast models will be improved by increases in the amount and geographic breadth of monitoring data, and regional standardization of sample collection and analysis;

- improved model forecasts will provide resource managers (e.g. recreational and commercial shellfish harvesting; bird and marine mammal strandings; aquaculture) and public health managers a more adequate basis for regulatory decisions, economic planning, and facility locations;

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- a regional HAB communication network would improve public education and reduce unwarranted concerns of tourists and coastal communities as advice on avoiding affected areas and shellfish becomes more effectively and routinely disseminated;

- improved predictive models on factors promoting HABs would help resolve the relative influences of natural and anthropogenic causes, and help guide mitigation strategies.

West Coast Regional HAB Summit

Workshop Goals: The goals of the Summit are to: 1) assess the present state-of-knowledge of the distribution, causes, and impacts of HABs along the West Coast; 2) identify the clients and needs for a coordinated Tri-State HAB monitoring, alert, and response network ; 3) identify necessary monitoring, alert, and response network elements, including how this system would link to the ocean observing networks; and 4) determine how to build a predictive HAB system for the U.S. West Coast region.

Workshop Drivers:

1. West Coast Governors' Agreement (WCGA) on Ocean Health: The WCGA Action Plan calls for a HAB workshop to reach consensus on the present state-of-knowledge and prioritize the information needed by decision makers to lessen the impacts of the HAB events on humans and critical marine resources. The *West Coast Regional HAB Summit* presents an opportunity for the West Coast HAB community to raise the profile of their efforts and concerns, and focus attention on future research and management needs. The agenda includes opportunities for public and media outreach, and policymakers, important target audiences for *Summit* outputs.

2. HABHRCA: The Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) and Monitoring and Event Response for Harmful Algal Blooms (MERHAB) programs are legislatively mandated through the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA), established in 1998, reauthorized in 2004, and currently undergoing a second reauthorization. In keeping with HABHRCA's directive to provide local and regional scientific assessments of HABs, one outcome from the *West Coast Regional HAB Summit* is a *West Coast Regional HAB Research and Action Plan* that will: 1) identify regional priorities for ecological and socio-economic research, their impacts, and technologies for monitoring, predicting, and PCM (prevention, control, mitigation), and 2) contain PCM and Event Response strategies to be implemented at local, State, and regional levels. Recommendations in this *Action Plan* will be used to guide research prioritization in NOAA/CSCOR's West Coast Regional ECOHAB, MERHAB, and the

newly developed PCM (Prevention, Control, and Mitigation of HABs) programs.

Summit Outputs:

1. Pre-meeting White Paper on the *Harmful Algal Blooms in the West Coast Region: History, Trends, and Impacts in California, Oregon, and Washington*

2. Reports from Breakout Sessions:
   a) *West Coast Regional HAB Monitoring, Alert, and Response Network: Goals, Users, and Management Needs* from Breakout Session I;
   b) *West Coast Regional HAB Monitoring, Alert, and Response Network: System Requirements and Design* from Breakout Sessions II and III;
   c) *Developing a West Coast Regional Forecasting System: Research Needs and Management Applications* from Breakout Session IV.

3. *West Coast Regional HAB Research and Action Plan*

Workshop Approach

The West Coast Regional Harmful Algal Bloom Summit will convene leading scientists and managers with knowledge of, and experience with, HABs issues on the coasts of California, Oregon, and Washington. A 3-day Workshop (10-12 February 2009) of invited participants will be followed by a Public Session on the evening of the third day. The Workshop will consist of plenary and breakout sessions designed to facilitate development of plans for a *West Coast Regional HAB Monitoring, Alert, and Response Network* and a *West Coast Regional Forecasting System*. Overviews of the goals, objectives, construct, and expected outcomes and benefits of the plans will be presented at the Public Session, which will culminate with an audience question-and-answer session directed at an expert panel.

The Introduction and Plenary Sessions will set the context and drivers for the Summit outputs (*West Coast Regional HAB Monitoring, Alert, and Response Network* and *West Coast Regional Forecasting System*) – the scope of the HAB problem in each state; the monitoring and forecasting infrastructure currently available to address the problem; potential advancements that tri-state regional coordination would lend to monitoring, response, and forecasting capabilities; and the potential benefits to coastal communities. Breakout Sessions I through III will lay the groundwork for developing a *West Coast Regional HAB Monitoring, Alert, and Response Network*, including determining goals, objectives, end users and management needs, science needs, system requirements, and Network design. Breakout Session IV then will extend the *Monitoring, Alert, and Response Network* design to complementary plans for a *West Coast Regional Forecasting System*.

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Guidance on Breakout Sessions

Breakout Session I: Identify the Desired Attributes and Informational Needs of a Coordinated Regional HAB Network

Goal: Identify the ideal characteristics of a Regional HAB monitoring, alert, and event response network.

Breakout groups will be formed based on the timeframe of information need, i.e. whether information generated from the Network would be needed by end users from: 1) real-time to within 48 hours ("Near-term"), 2) 48 hours to weekly ("Medium-term"), or 3) weekly to yearly ("Long-term"). Examples of different priorities in timeframe of information access include: a) shellfish harvesters need HAB alerts within 48 hours to prevent collection of contaminated products; b) monitoring on a 48-hour to weekly basis may be appropriate for the assessment of seasonal trends in HAB distribution; c) weekly to yearly data are useful for assessing long-term annual trends. Each breakout group will address the following questions:

- Who are the users of such a system, and what are the management needs?
- What are the short- and long-term goals and objectives of the system?
- What are the informational needs from such a network?
- What types of data are required to fill these needs?

Breakout Session II: Developing a Coordinated Regional HAB Network, Part 1 – Science Needs

Goal: To determine the science needs to develop a coordinated West Coast Regional HAB Monitoring, Alert, and Response Program that fills the informational needs identified in Breakout Session I.

For this session, science needs will be discussed in three breakout groups based on the type of measurements needed: 1) remote sensing; 2) physical measurements; 3) biological measurements. Questions to be addressed include:

- What are the parameters to be measured?
- What are the necessary spatial and temporal allocation of that sampling effort?
- How can data produced from the multiple types of sampling be integrated into a comprehensive nowcasting system?

Breakout Session III: Developing a Coordinated Regional HAB Network, Part 2 – System Requirements and Design

Goal: To determine the system requirements for achieving the science needs identified in Breakout Session II, and design the coordinated West Coast Regional HAB Monitoring, Alert, and Response Network.

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This Breakout Session will determine the system requirements needed to design the Network, and will include work groups addressing different Network components, including: 1) Monitoring (includes measurement, data management); 2) Alert and event response; and 3) Communications – outreach and education. Each group will address the following questions:

- What are the system requirements of the Network?
- How can a coordinated HAB network be designed to meet the needs of the overall community?
- How can the current HAB programs provide a basis for this design?
- How can a HAB network be integrated with the OOS' programs?
- What aspects of the OOS' programs can be used in the design and implementation of a network?

Breakout Session IV: Regional Forecasting System

Goal: Identify how to extend the design established in Breakout Session III to create a forecasting system for HABs.

The work groups in this Breakout Session represent regimes where different areas of the coast have common HAB characteristics that would be amenable to nsimilar predictive modeling approaches. These include: 1) Open Coast (Oregon and northern California); 2) Coastal Hotspots (Juan de Fuca eddy, Heceta, Monterey and the Channel Islands); and 3) Urban and Estuary Regions (San Francisco Bay, Southern California, Puget Sound). Each group will address the following:

- What types of data and systems are required to create a regional forecasting system for HABs?
- How could a forecasting system be implemented to the strategy design suggested in Breakout Session III?
- What are the impediments for developing a regional forecasting model?

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